This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

**Usage guidelines**

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

+ *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.

+ *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.

+ *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.

+ *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

**About Google Book Search**

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at `http://books.google.com/`

$B 16 462

SOCIETY
OF ENGINEERS.

Digitized by Google

# Premium.

## Society of Engineers.

SESSION 1865

Presented to

Lewis Aldrick

for his Paper on

Giffard's Injector

read before the Society

on the 18th December 1865

W. T. Carrington President

W. H. Williams Hon. Secretary.

Digitized by Google

THE LIBRARY
OF
THE UNIVERSITY
OF CALIFORNIA

PRESENTED BY
PROF. CHARLES A. KOFOID AND
MRS. PRUDENCE W. KOFOID

Digitized by Google

Digitized by Google

Digitized by Google

Digitized by Google

# HISTORY AND PROGRESS

OF

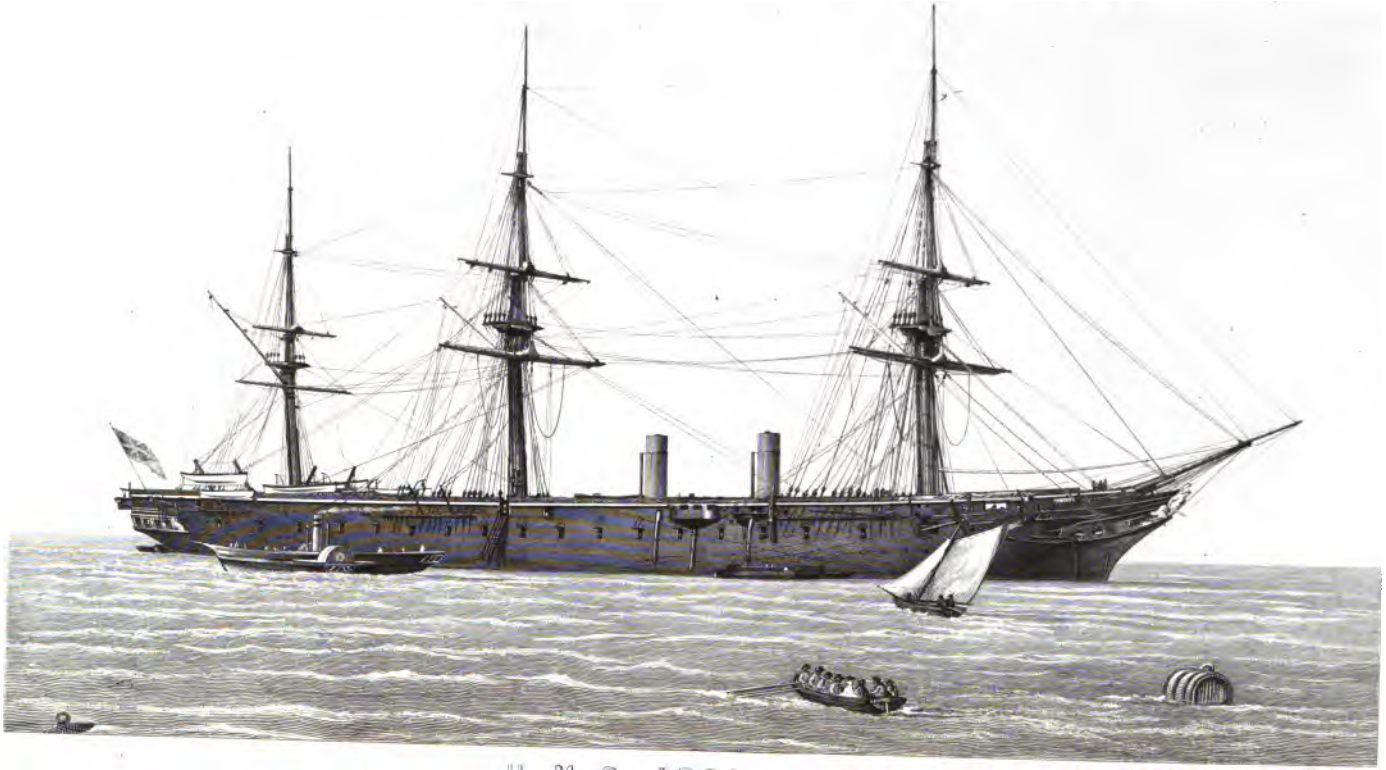
# IRON SHIP BUILDING.

Digitized by Google

LONDON
PRINTED BY SPOTTISWOODE AND CO.
NEW-STREET SQUARE

Digitized by Google

Digitized by Google



H. M. S. IRON CLAD
"WARRIOR."

H. Adlard, sc.

Digitized by Google

# TREATISE

ON

# IRON SHIP BUILDING:

ITS

# HISTORY AND PROGRESS

AS COMPRISED IN A SERIES OF EXPERIMENTAL RESEARCHES ON THE LAWS OF STRAIN; THE STRENGTHS, FORMS, AND OTHER CONDITIONS OF THE MATERIAL; AND AN INQUIRY INTO THE PRESENT AND PROSPECTIVE STATE OF THE NAVY, INCLUDING THE EXPERIMENTAL RESULTS ON THE RESISTING POWERS OF ARMOUR PLATES AND SHOT AT HIGH VELOCITIES.

BY

WILLIAM FAIRBAIRN, ESQ., C.E.
LL.D., F.R.S., F.G.S., &c.
CORRESPONDING MEMBER OF THE NATIONAL INSTITUTE OF FRANCE, AND OF THE ROYAL ACADEMY OF TURIN
CHEVALIER OF THE LEGION OF HONOUR;
ETC. ETC.

LONDON:
LONGMANS, GREEN, AND CO.
1865.

Digitized by Google

U-2469-136

Digitized by Google

VM146
F3

TO

HIS GRACE

# THE DUKE OF SOMERSET, K.G.

ETC. ETC. ETC.

FIRST LORD OF THE ADMIRALTY,

THIS WORK ON IRON SHIP BUILDING

IS RESPECTFULLY INSCRIBED

BY

THE AUTHOR.

Digitized by Google

Digitized by Google

# PREFACE.

In the production of this work I have found it convenient to divide it into parts; and as each part may be taken as a separate treatise, a brief analysis of each particular subject, as it follows in consecutive order, may be of service to the reader.

I. The Introductory Notice contains a brief history of the rise and progress of Naval Construction since the time when Iron was first employed for that purpose. This embraces almost entirely my own personal experience; and, as one of the pioneers and first experimentalists who proved the value of Iron applied to Shipbuilding, I am probably competent to write on the subject with some authority.

II. The whole of this division—comprised in Chapters II., III., IV., and V.—treats of the Law of Strains, and the properties of the material—how it should be disposed in the construction of vessels in order to meet the force of wind and sea; and how the material in the different parts should be proportioned and distributed so as to equalize their powers of resistance to the alternation of strains which the different parts undergo when the ship is afloat. As a guide to Iron Ship Building, I have considered it necessary to give an analysis of he experiments on the strength and other properties of plates, angle-iron, &c. The results of this analysis are chiefly taken from my own experiments,* and from those of the late Professor

* See 'Philosophical Transactions,' Part II. (1850), page 677.

M310457

Digitized by Google

Hodgkinson, to whom science is indebted for many new and important discoveries.

These experiments embrace almost every known mechanical property of Iron;* and the knowledge thus obtained has furnished data for the construction of ships, and other structures employed in the useful and industrial arts. The ultimate powers of resistance of Iron to tension, compression, torsion, &c. are taken from the same source; and to these reference may be made for guidance in the selection and distribution of the material when applied to the purposes of Shipbuilding.

Another important question to which I have alluded is the Jointing of Iron Plates, and the Form of Joints required in Shipbuilding. Here I have endeavoured to show what kind of riveted joint is requisite in order to attain the maximum powers of resistance in the longitudinal and transverse joints; and, moreover, to impress on the minds of Naval Architects the necessity of careful attention to experimental facts, which are of much greater value in the art of Shipbuilding than most persons imagine. A single defective joint may endanger the safety of a ship; how much greater, therefore, must be the danger if the principle throughout be unsound, and the whole of the joints of an imperfect character! A sound system of riveting is a most important desideratum in shipbuilding, and on no account should it be left to the judgment of ignorant and irresponsible persons.

To the frames and ribs of ships I have directed the same careful attention; and although it may be difficult to estimate the strains to which they are subject, it is nevertheless necessary, in order to give rigidity and strength to the hull, that strong ribs should be provided to retain the vessel in shape, and to receive the outer sheathing or plating. On these points I have,

* Mr. Kirkaldy published, a few years since, a detailed series of experiments on Iron and Steel, in which will be found much useful information on the strengths and other properties of these materials.

Digitized by Google

however, to refer the reader to the eighth division, where he will find the question more fully investigated.

In this division I have introduced a series of experimental researches on Cellular Constructions, first exhibited in the construction of the Britannia and Conway Tubular Bridges, and more recently in H.M.S. 'Bellerophon.' These researches will, I trust, be found of great value in Shipbuilding. For many years I have earnestly called public attention to this new system, believing it to be the strongest and most economical form of construction for seagoing vessels. It is the only true form for resisting the force of compression: and the form of the hull and upper deck gives double security, not only from the superior strength of the parts, but from the additional security of a double bottom, rendering a vessel so constructed what is technically called an *unsinkable* ship.

III. This division—Chapter VI.—treats of the comparative merits of wood and iron-built ships; and I have given examples, deduced from experiment, showing the superior advantages of the latter construction. From the facts recorded, it is evident that the superior strength of iron, as compared with the very best description of oak or teak, is sufficient to establish its claims as the best kind of material for shipbuilding. But this is not all; for when we consider the way in which the parts are united, and the form in which the junction of the plates is effected by rivets, the whole of the sheathing becomes almost homogeneous, and the strength nearly equal to that of the solid plate. On this principle a carefully-riveted iron ship may be looked upon as jointless, and hence its value as a strong and durable structure. In short, an iron ship, with its iron sheathing riveted to the frames, may be considered as uniform in its powers of resistance, and superior to anything yet accomplished by any other material with which we are acquainted.

Wood sheathing, when attached to iron ribs, is, to say the

Digitized by Google

least of it, a weak and unsatisfactory construction. Composite structures of this kind, where strength is required, are never safe, for the two materials are so widely different in character as to produce by their union a source of weakness of a most unsatisfactory description; and they are therefore not to be compared with vessels formed exclusively of iron, nor even with those entirely composed of wood. It is for these reasons I have been unable to recommend this kind of construction, excepting only for special purposes where great lightness is required, such as for river-boats, and in countries where timber is plentiful and cheap.

IV. From the title of this work, it may be fairly assumed that it is confined exclusively to the principles and practice of Iron Ship Building. This is not, however, the case, as I have considered it essential—in Chapter VII.—to examine the different forms of construction of ships of war, as recommended by the Controller of the Navy, Rear-Admiral Robinson, Mr. Reed, Naval Constructor, Captain Cowper Coles, and Mr. McLaine of Belfast. To these and other systems I have in this section given special attention, as also to armour-plating and the armaments essential to efficiency in the double capacity of attack and defence. This is a large and unsettled question; there is yet much to learn, and much yet to be accomplished, before it can be satisfactorily determined which is the best size and form of ship, and the safest and most effective gun.

V. On the question of Ordnance, which I have considered in this division—Chapter VIII.—the makers themselves are not agreed as to the penetrating powers of their respective guns. Sir William Armstrong, in a letter to 'The Times,' speaks of the fallacy of the present system of calculating the force of guns by the weight of the shot, and neglecting the quantity of powder contained in the charge. That the law which governs, within certain limits, the penetration of armour-plates, depending on

Digitized by Google

the *vis viva* of the shot and the charge of powder, is now recognised; and it is satisfactory to learn that much clearer conceptions are beginning to be entertained on this subject than heretofore.

To arrive at correct conclusions, I have found it necessary to refer not only to my own experiments and those of my colleagues of the Iron Plate Committee, but to collect from other sources such other general information as I could obtain on the construction of Ordnance. The numerous improvements that have been effected in the construction of guns in this country have not been exclusively confined to the experiments of Sir William Armstrong and Mr. Whitworth; but experimental researches in the same direction have been made all over Europe and America, where guns of great weight and caliber have been constructed with more or less success. I have devoted several pages to Cast-iron Guns, and the mode of casting them as adopted in America; and the experiments so ably conducted by Major Wade are so important, that I have not hesitated to give short extracts from his writings for the purpose of exhibiting the improvements that have been made in the preparation of the metals, and on the principle of casting, construction, &c., as practised in the manufacture of the Dahlgren and Parrott guns.

VI. In this division—Chapter IX.—the properties of Iron Armour Plates, and their resistance to projectiles at variable velocities—a question which has engaged the attention of the Government for several years—have been considered. In 1859 the Iron Plate Committee was appointed, and it fell to my lot, as a member of that Committee, to make an elaborate series of experiments, to ascertain, by statical pressure, the properties of a great variety of plates, from different makers, in their powers of resistance to tension, compression, shearing, punching, &c. The results of these experiments will be found exceedingly interesting, not only as regards the quality of the material and the ductility which may be given to it in the process of manufac-

Digitized by Google

ture, but the law of penetration has been determined from these data, which has been found to agree with results derived from the impact of shot. In this section will also be found an abstract of the tabulated results, including a description of some of the targets representing the sides of different vessels, and the weight of ordnance, charges of powder, with distance of range, &c., by which they were perforated. These and other conditions, as regards fastenings, wood-backing, &c., will show the reader what pains had been taken by the Admiralty in arriving at correct and satisfactory data, before coming to a final decision relative to the form, size, and quality of plates requisite to resist a force of impact.

VII. This division—Chapter X.—treats of the resistance of shot and shell when fired against iron armour-plates. In the earlier experiments—with the exception of a few small steel projectiles, weighing only 0·34 lbs., used in the wall-piece gun—cast and wrought iron were employed. Mr. Whitworth fired steel bolts from his gun, which penetrated the 4½-inch plates of the 'Trusty,' but it was only towards the close of the experiments that steel was recommended as the material for projectiles calculated to perforate iron plates. The whole of the shot composed of cast-iron, when fired against iron plates, were broken in pieces by the force of their own momentum, and the fragments dispersed in every direction; wrought-iron, from its ductility and plastic nature, was distorted in form, and rendered totally inoperative as a vehicle of penetration. The results of statical pressure and punching gave, however, general laws relative to the resistance of plates to a force tending to rupture them; and it will be found, on referring to this part of the subject, that cast and wrought-iron service-shot are far from fulfilling the highest conditions assumed in the formula, as the work lost in distorting and breaking up the shot for each class is equivalent to a proportional part of the whole work accumulated in the projectile.

Digitized by Google

VIII. To the question of the construction or build of Iron Ships, I have—in Chapters XI. and XII.—given more than ordinary attention, making a distinction between those intended for commerce and those employed in war. In treating of the former, I have given practical illustrations for the purpose of showing what I consider the best principle of construction; and in every case where it can be adopted, I have recommended *the cellular system and double bottom.* I have considered this essential to the security not only of ships of war, but of every other class of seagoing vessels. I have also ventured to make suggestions in regard to the present system of Naval Construction in Her Majesty's Dockyards, both as respects the frames, plating, riveting, &c., and the deck-stringers and other adjuncts necessary to a sound and perfectly-constructed ship.

These suggestions are given as deductions from experimental data rather than the results of a favourite theory; and I venture to hope that they may be found useful in directing the attention of builders to those laws of construction by which we arrive at security as well as economy.

In shielding our ships of war from the effects of an enemy's shot, I must confess that—taking into account the progressive improvements in the power of guns, which have kept pace with the increased resistance of plates—we are now as nearly as possible in the same relative position as the Navies of this and other countries were fifty years ago; and as it appears that we cannot cover and protect the whole of a ship with a sufficient thickness of plates, the next best thing to do is to take our chance, and let the shot *go right through.* This, under certain conditions, I have recommended to be done; but with a saving-clause, that the vessel should be protected by a line of thick armour-plating above and below the average line of flotation, and that exclusively for the safety of the ship.

IX. This division—Chapter XIII.—may be considered simply as a recapitulation of that part of the work which treats of the

Digitized by Google

changes which are in progress relative to the construction of ships of war, by which this and every other country are compelled to sacrifice the existing two and three-deckers, and adopt an entirely new system of construction—to make a transfer, in fact, from the present wooden ships to those of iron, and to give them new forms and new combinations calculated to meet the changes and other requirements of the times.

I have advocated the superior power and increased security of vessels constructed of iron; and, considering the risks of fire from shells—which are now made to penetrate armour-plates—it is desirable that this material should be exclusively employed in the formation of ships of war.

Having also noticed what has been done in France and America, I have come to the conclusion—considering the superior resources of this country—that the Navy of Great Britain and Ireland should, as regards efficiency, power, and speed, continue to surpass that of any other country having the least claim to consideration as a maritime power.

X. This division—Chapter XIV.—contains a valuable treatise, by my friend Mr. Tate, on the Strength of Materials considered in relation to the Construction of Iron Ships, and I am indebted to that gentleman for the deduction of formulæ from the experiments to which I have referred.

My thanks are also due to my assistant, Mr. E. W. Jacob, for the able manner in which he has executed the drawings, and the attention he has bestowed in the revision and arrangement of the Tables.

To Admiral Robinson the Controller, and Mr. Reed the Constructor of the Navy, I am also indebted for a sectional drawing of the hull of H.M.S. 'Bellerophon,' and to his Grace the Duke of Somerset, and the Board of Admiralty generally, for the opportunities afforded me in visiting the Dockyards during the building of that vessel.

In conclusion, it is not without diffidence that I submit this

Digitized by Google

work to public consideration. Its origin may be traced to the experimental researches in which for many years I have been engaged, some of which have appeared in the 'Philosophical Transactions,' the 'Transactions' of the British Association for the Advancement of Science, and other Institutions to which I have communicated them in the shape of Papers. The greater portion has, however, been written from my own practical experience, and, as far as possible, I have endeavoured to avoid prolixity and repetition. Throughout the work I have sought to inculcate sound principles of construction, and to urge upon constructors the necessity of carrying out this principle, in order to render the Iron Ship what I believe she is destined to become —a bulwark of strength in the defence and security of the British Empire!

W. F.

MANCHESTER: *Oct.* 15, 1865.



Digitized by Google

Digitized by Google

# CONTENTS.

## CHAPTER I.


HISTORY OF THE RISE AND PROGRESS OF IRON SHIP BUILDING:— PAGE

Introductory Notice . . . . . 1
First Construction of Iron Canal Boats . . . . . 2
Building of the 'Aaron Manby' . . . . . 2
New Discovery in Canal Navigation . . . . . 2
Introduction of Steam on the Locomotive principle in Iron Vessels, through recommendations deduced from the result of Experiments on the Forth and Clyde Canal . . . . . 3
Notice of the 'Alburka,' built by Messrs. Laird & Co. . . . 4
Advancements consequent to the superiority of Iron over Wooden Vessels 4
Recent Improvements and Advancements due to the labours of Brunel, Russell, Laird, Vernon, Napier, and others . . . . . 5
Application of Iron to the Construction of Ships of War . . 5
Fresh impetus given to the Construction of Iron Ships of War by the introduction of Armour-plates by the Emperor of the French . 6


## CHAPTER II.


ON THE STRAINS TO WHICH A SHIP IS SUBJECTED WHEN AFLOAT:—

When supported on the crest of Two Waves, one at the Bow and the other at the Stern . . . . . 9
When supported by a Wave at Midships . . . . . 9
When supported by a Wave near the Stem or Stern . . . 9
Calculation of the Displacement of Vessels . . . . 11
Consideration of the Nature and Intensity of the Strains . . 11
Rankine's investigation of the most severe Straining Action to which a Vessel can be subjected when afloat . . . . . 12
Effects of Vibratory Action and Alternate Strains of Tension and Compression on Wrought Iron . . . . . 13
Safe working load of Wrought Iron . . . . . 14




Digitized by Google

PAGE

Method of ascertaining the Intensity of the Strain on the material of a Ship by treating it as a hollow Beam . . . . . 15

Value of the moment of the Weight of a Ship to produce Transverse Fracture, given in terms of the Length and Position of the Centre of Gravity for the various positions in which she may be placed . 16

## CHAPTER III.

### ON THE PROPERTIES OF IRON CONSIDERED AS A MATERIAL FOR SHIPBUILDING, AND THE RESISTANCE OF WROUGHT-IRON PLATES TO THE FORCE OF EXTENSION:—

Division of the subjects treated of in the Volume . . . 18

Distribution of Iron Ores . . . . . 19

Treatment of Iron after passing the Smelting Furnace . . 19

I. ON THE STRENGTH OF PLATES WHEN TORN ASUNDER BY A DIRECT TENSILE STRAIN IN THE DIRECTION OF THE FIBRE, AND WHEN TORN ACROSS IT:—

Table of the Strength of Iron Plates when torn by a direct Tensile Strain . . . . . 21

Tensile Strength of Wrought-Iron Bars . . . . . 22

II. ON THE DUCTILITY, ELONGATION, AND DYNAMIC RESISTANCE OF WROUGHT IRON:—

Table of the Statical Breaking Strain of Iron of various thicknesses from different Manufacturers . . . . . 23

Table of the Ultimate Elongation per Unit of Length of Wrought-Iron Plates . . . . . 25

Table of the Dynamic Resistance or Work done in causing Rupture in Wrought-Iron Plates . . . . . 26

Deductions from the Tables . . . . . 26

Law relating to the Elongation of Wrought-Iron Bars . . 30

III. ON THE STRENGTH OF THE JOINTS OF PLATES WHEN UNITED BY RIVETS AS COMPARED WITH THE STRENGTH OF THE PLATES:—

On the requisites of Good Riveting:—

I. PUNCHING:—

Form of Punch, Coincidence of Holes, &c. . . . 32

II. RIVETING:—

Strength of the Single Riveted Joint . . . 36

Strength of the Double Riveted Joint . . . 36

Strength of Flush or Butt Joints . . . . 38

Table of the Results of Experiments on Riveted Joints . 39

Ratio of the Comparative Strength of Joints and Plates . 40

Digitized by Google

PAGE

System of Riveting developed in the Construction of the Britannia and Conway Tubular Bridges . . . . 41
Another System of Covering Joints . . . . 42
Defects produced in Riveting from the want of Coincidence of the Punched Holes . . . . . 43
III. Rivets:—
Table exhibiting the strongest Forms and best Proportions of Rivets and Riveted Joints . . . . 45

## CHAPTER IV.

### ON THE RESISTANCE OF PLATES AS APPLIED IN DIFFERENT FORMS TO THE FORCE OF COMPRESSION:—

Resistance of Steel, Cast and Wrought Iron, and Wood to a Force of Compression . . . . . 48
Resistance of Flat and Rounded Columns to a Force of Compression . 49
Table of the Resistance of Wrought-Iron Plates to a Crushing Force . 53
Table of the Resistance of Wrought-Iron Circular Tubes to a Force of Compression . . . . . 54
Table of the Resistance of Rectangular Tubes to a Force of Compression 55
Professor Hodgkinson's Method of deriving Natural Laws from the Results of Experiment . . . . . 55
Deductions from the Analysis of Experiments . . . 59

## CHAPTER V.

### ON THE STRENGTH AND DISTRIBUTION OF THE MATERIAL OF WROUGHT-IRON PLATES AND FRAMES AS APPLIED TO THE CONSTRUCTION OF IRON SHIPS:—

The Sectional Area of the 'Victory' contrasted with that of the 'Warrior' . . . . . 65
Rules to be observed in the Construction of Iron Ships to obtain the maximum conditions of Strength . . . . . 66
Considerations with regard to the Position and Intensity of the Strains deduced from the treatment of a Ship as a hollow Girder . . 69

## CHAPTER VI.

### THE COMBINATION OF IRON AND WOOD IN THE CONSTRUCTION OF SHIPS:—

Investigation of the Defects arising from the Combination of Wood and Iron in Shipbuilding . . . . . 71
Table of the Comparative Values of Wood and Iron submitted to a Tensile Strain . . . . . 72

Digitized by Google

PAGE

Tensile Strength of a Model representing the Sheathing of the sides of a Ship . . . . . 74
Tensile Strength of the Timber of which the Model was composed . 76
Resistance of Wrought-Iron Plates to a force tending to burst or rupture them . . . . . 78
Resistance of Planks of Wood to a force tending to burst them . 79
Comparative Strength of Wood and Iron submitted to a Compressive Strain . . . . . 81
General Method of Constructing the Frames and Ribs of Ships . 82
Strength of the Frames and Ribs of Iron Ships . . . . 82
The Strength of uniform Wrought-Iron Beams of different forms to support the Sides and other parts of Vessels . . . 85
The best Sectional Form of Beams for the Decks of Ships . . 91
Deductions from the Experiments . . . . . 93

DIFFERENT METHODS OF CONSTRUCTING SHIPS OF IRON AND WOOD:—

The Composite Construction . . . . . 95
System of strengthening the Composite Construction . . 96
Description of the System advocated by Mr. M'Laine . . 97

## CHAPTER VII.

ON THE VARIED FORMS OF CONSTRUCTION OF SHIPS OF WAR AND THEIR ARMAMENTS:—

The greatly increased Progress in the Manufacture and Power of Ordnance render necessary a more extended investigation of the Laws relating to the Resistance of Plates to the Impact of Shot . . 103
Installation of the Iron Plate Committee, and General Outline of their Researches . . . . . 104
Effect produced on Cast-Iron Shot when fired against Wrought-Iron Armour Plates . . . . . 108
Effect produced on Wrought-Iron Shot when fired against Wrought-Iron Armour Plates . . . . . 109

EXAMINATION OF THE DIFFERENT SYSTEMS OF CONSTRUCTION:—

Reed's Midship System of Construction . . . . 111
System of Scott Russell, Grantham, and others . . . 116
Coles' Turret System . . . . . 116
Comparison of the Midship and Turret Systems . . . 118
M'Laine's End-on System . . . . . 122
Proposed System of Construction . . . . . 126
Examination of the Principal Merits of the Proposed System of Construction . . . . . 130

Digitized by Google

PAGE

CHAPTER VIII.

ON THE PROPERTIES OF CAST AND WROUGHT IRON AND STEEL AS MATERIALS FOR THE CONSTRUCTION OF ORDNANCE:—

Comparison of the Properties of American and English Irons . 136
Description of the Method adopted in Casting and Cooling Columbiad Guns . . . . . 140
Mathematical Investigation of the Strains produced in Guns during Cooling . . . . . 143
The Longevity of the Strains produced in the passing of Metals from the Fluid to the Solid State . . . . . 147
Armstrong's System of Manufacturing Wrought-Iron Guns . . 150
The Whitworth, Blakeley, Mackay, and Palliser Systems . . 151

CHAPTER IX.

ON THE PROPERTIES OF IRON ARMOUR PLATES, AND THEIR RESISTANCE TO SHOT AT HIGH VELOCITIES:—

The Best Method of applying Armour Plates a question yet to be solved . . . . . 153
Admiral Porter's Report on Armour-plated Ships . . . 153
Effect of Shot on Iron Armour Plates of different degrees of Ductility. 156
Summary of Results of the Tensile Strength of Plates . . 158
Summary of Results of the Resistance of Plates to Indentation . 159
Summary of Results of the Resistance of Plates to Punching . 160
Description of the 'Lord Warden' Target . . . 161
Nature of Ordnance, Weight of Shot, &c. fired against the Lord Warden' Target . . . . . 162
Form of the 'Lord Warden' Target . . . . 167

CHAPTER X.

ON THE IMPACT AND RESISTANCE OF SHOT AND SHELLS FIRED AGAINST ARMOUR PLATES:—

Investigation of the Theoretical Laws relating to the Work accumulated in and expended by Shot discharged from Ordnance . . 170
Deduction of Formulæ relative to the Resistance of Plates to Impact from the Results of Experiments on the Perforation of Plates by Statical Pressure . . . . . 173
Application of the Formulæ to the Experiments at Shoeburyness . 175
Comparison of the Formulæ with Results obtained from the Armstrong Gun . . . . . 176
Comparison of the Formulæ with Results obtained from the Whitworth Gun . . . . . 177
The Work done in Foot Pounds on different Targets . . 179

Digitized by Google

PAGE
Description of the 'Warrior' Target . . . . . 179
Size of Guns, Nature of Projectiles, &c. fired against the 'Warrior' Target . . . . . 181
Experiments on Plates supported by Backing . . . . 181
Mean Value of Indentations of Plates without Backing . . 182
Investigation of the Mechanical Properties of Mr. Stirling and Dr. Price's Cast-Iron Shot . . . . . 183
The Effect of Statical Pressure on different kinds of Shot . . 187
Summary showing the Work done by Statical Pressure on Cast, Wrought-iron, Steel, and Lead Shot . . . . . 189
The Nature of the Injury done to Shot, and the Effect produced by the Impact of Shot on a section of the 'Warrior' Target . . 191
Deductions from the Tables . . . . . 194

## CHAPTER XI.

### ON THE PRACTICAL CONSTRUCTION OF IRON SHIPS:—

I. Merchant Ships:—

Construction of the Hull, Sides, and Decks . . . . 199
Construction of the Upper and Lower Deck Beams . . . 202
Construction of the Sternpost and Rudder . . . . 205

II. Ships of War:—

1. Tonnage of Ships of War . . . . . 207
Proposed Shield Ship . . . . . 209

2. General Principles of Construction:—

The 'Penelope' . . . . . 211
The 'Bellerophon' . . . . . 213
The 'Warrior' . . . . . 218
Proposed Iron Vessel with a Water Backing . . . . 222
Size, Tonnage, &c. of some Armour-plated Vessels of Her Majesty's Navy . . . . . 224

## CHAPTER XII.

### ON THE PRACTICAL CONSTRUCTION OF IRON SHIPS (continued):—

American Ships:—

Construction of the 'New Ironsides' . . . . . 226
Construction of the 'Chickasaw' . . . . . 227
Construction of the 'Nauset' . . . . . 228

Digitized by Google

PAGE

CHAPTER XIII.

ON THE COMPARATIVE MERITS OF SHIPS OF WAR:—

RECAPITULATION OF THE FOREGOING:—

Vessels Constructed of Iron . . . . . 231
Vessels Active at Sea . . . . . 233
Vessels only Partially covered with Armour Plates . . 233
Vessels of Cellular Construction with Double Bottom . . 235

CHAPTER XIV.

ON THE STRENGTH OF MATERIAL CONSIDERED IN RELATION TO THE CONSTRUCTION OF SHIPS OF WAR:—

PRELIMINARY PRINCIPLES:—

Elongation and Compression . . . . . 237
The Neutral Axis of a Beam . . . . . 239
Conditions of Transverse Rupture . . . . 241
Conditions necessary to be observed in Constructing a Beam of Maximum Strength with a given amount of Material . . . 243
To change the Axis of Moments . . . . 243

TRANSVERSE STRAINS PRODUCED ON BEAMS UNDER VARIOUS CONDITIONS:—

When the Pressure is applied in the Middle of a Beam supported at the Ends . . . . . 244
When the Pressure is applied at various Points of a Beam supported at the Ends . . . . . 245
When the Load is distributed uniformly throughout the Length of the Beam . . . . . 245
When the Beam is Fixed at one extremity and Loaded at the other . 246
When the Load is distributed uniformly throughout the Length of a Beam Fixed at one extremity . . . . 246
When any Number of Pressures are applied to a Beam . . 247
To find the point of Maximum Strain in a Ship unequally Loaded throughout its Length . . . . . 249
When the Load has the form of a Trapezoidal Figure . . 251
When a Beam is supported by two Props at Equal Distances from its Extremities . . . . . 252
Recapitulation of the Results of the foregoing Analysis . . 253

STRENGTH, &C. OF BEAMS:—

When the Neutral Axis passes through the Centre of the Section . 255
Hollow Rectangular Beams with Double Flanges . . . 256
When the Beam is composed of a Series of Cells . . . 257
Cylindrical Beams . . . . . 258
When the Beam is a Hollow Cylinder . . . . 259
To determine the Comparative Strengths of Circular and Square Cells . 260



Digitized by Google

| FIGS. | | | PAGES |
|---|---|---|---|
| 49 | —Illustrative of the | 'Royal Sovereign' Turret Ship | 117 |
| 50 to 55 | „ | The comparative merits of Reed's and Coles's Systems | 118, 119, 120 |
| 56 to 58 | „ | M'Laine's System | 123, 124 |
| 59 | „ | Improved System | 127 |
| 60 to 62 | „ | The Nature of the Fracture of Armour-plates of different degrees of ductility | 156, 157 |
| 63 | „ | The 'Lord Warden' target | 167 |
| 64 to 65 | „ | The 'Warrior' target | 179, 180 |
| 66 to 71 | „ | Nature of the Fracture of different kinds of Shot by statical pressure | 187 |
| 72 to 74 | „ | Effect of Impact on Shot and Targets | 188, 191, 192 |
| 75 to 81 | „ | Construction of Merchant Vessels, | 199, 200, 201, 202, 205 |
| 82 to 83 | „ | Proposed Shield Ship | 210 |
| 84 to 86 | „ | The 'Penelope' War Frigate | 211, 213 |
| 87 to 90 | „ | The 'Bellerophon' War Frigate | 215, 216, 217 |
| 91 | „ | The 'Warrior' War Frigate | 219 |
| 92 | „ | Proposed Iron Ship with Water Backing | 222 |
| 93 | „ | American Ship 'New Ironsides' | 227 |
| 7 to 98 | „ | American Monitor 'Nauset' | 229 |
| 99 to 125 | „ | Strength of Material as applied to the Construction of Iron Ships | 239 to 282 |
| A to E *Appendix* | „ | Portions of the Fracture of Experimental Guns, | 292, 293 |


CORRIGENDA.

The Table on page 137 should have been numbered Table I.

„ „ 138 „ „ Table II.

Digitized by Google

# A TREATISE

ON

# IRON SHIP BUILDING.

## CHAPTER I.

### A SHORT HISTORY OF THE RISE AND PROGRESS OF IRON SHIP BUILDING.

IRON SHIP BUILDING is a branch of industry of recent origin, and its history is a tale that is soon told. Towards the close of the last century, or anterior to the year 1784, when Cort first introduced his invention of rolling plate and bar iron, there was nothing in the form of iron plates of which ships or vessels could be made. Shortly before that time, when Watt was engaged with his steam-engine, the only material at his command for his boiler, in which to generate steam, was hammered copper plates or cast iron. Hammered iron plates were occasionally made, but seldom used, unless for special purposes; and it was not until the introduction of rolls that anything in the shape of iron plates could be obtained. At that time, and for several years subsequently, little or nothing was done to encourage the manufacture; but the new process of rolling simplified the operation, and gave greatly increased facilities for the manufacture of this important article of commerce. They were first applied to the construction of boilers (those of the haystack form were made as early as 1786), which were chiefly employed for raising steam for the atmospheric pumping-engines



Digitized by Google

of Cornwall and the collieries of Northumberland and Durham. More recently, or about the same date, Mr. Watt introduced the waggon-shaped boiler for his reciprocating sun-and-planet-wheel engine, but we have no traces of iron boats or ships at a date antecedent to that of Cort and Watt.

At the commencement of the present century it is more than probable that the first construction of iron canal boats took place, and we have evidence of their existence in Staffordshire about the years 1812 or 1813. From that time to the present iron boats have been successfully employed on canals.*

From 1812 to 1822—to use a familiar expression—there was an interregnum of progress for a period of ten years, and we hear nothing of iron, as a material for ship building, till the Horsely Company built the 'Aaron Manby,' which was sent to London in sections, reconstructed in one of the docks, and navigated to Havre and Paris by the late Admiral Napier.

It was supposed that the success of the 'Aaron Manby' would have stimulated exertions in the same direction, but important discoveries, like other things of great magnitude, require time to bring them to maturity; and another interregnum ensued from 1822 to 1830, when a new discovery was made by Mr. Houston, of Johnstone, near Paisley, in which it was found that a light boat drawn by two horses had sufficient power to convey passengers on a canal at the rate of from nine to ten miles an hour. This discovery was made at a time when new and important events, forming an era in the history of transit on railways, burst unexpectedly upon the public;—we allude to the experimental tests and competitive trials of locomotive engines at Rainhill. The results of these trials created alarm in the minds of all the canal proprietors of the kingdom. They became anxious about their property, and the speed of ten miles an hour, as attained by Mr. Houston in his gig boat, was the

* Mr. Grantham informs me that an iron barge was made in 1787, and it has been stated that another was built for the Severn in 1789. About 1824, when the 'Aaron Manby,' iron steamer, was constructed, another small steamer was built, and sent to the Shannon, by Mr. Grantham's father; and in 1829-30 Mr. Grantham was present at the experiments with the twin boat on the Irwell.

Digitized by Google

only gleam of hope left to enable them to meet, with anything like success, the alarming and powerful competition of the rail and locomotive.

Things were in this state when the Governor and Council of the Forth and Clyde Canal employed the author to institute a series of experiments to determine the law of traction and to account for the phenomenon of the absence of surge at high velocities on canals. These experiments were interesting and conclusive, and the report was shortly afterwards published, at the request of the Forth and Clyde Canal Company.* In this report will be found a detailed account of the experiments, and the principles to which they gave birth, together with certain plans for improving the navigation, the most prominent of which were the introduction of iron vessels, and steam on the locomotive principle, in the place of horses, as a motive power on canals. Acting upon this recommendation, four iron vessels were made at Manchester: one a twin boat with the paddle-wheel in the centre; and a second, the 'Lord Dundas,' with the paddles recessed in what is called the 'dead wood' of the stern. The first was an experimental boat, and the second, also of iron, plied for several years as a passage-boat between Port Dundas and Lock 16.

Simultaneous with these vessels, another and a larger vessel, 84 feet long and 14 feet beam, with recessed paddles in the stern, was built in Manchester, in 1831, and navigated through the locks of the Mersey and Irwell navigation to Liverpool; from thence to Greenock; and, to the best of our knowledge, this was the second iron vessel that ever put to sea—if we except the 'Lord Dundas' light boat, which performed the voyage from Liverpool to Glasgow in the previous year. This vessel (the 'Manchester') was for several years employed as a coasting vessel, carrying goods and passengers between Port Dundas, Grangemouth, and Dundee.

During the time of these constructions Messrs. John and Macgregor Laird were engaged in similar undertakings for the Irish canals, and were present with Mr. Grantham and others at most of the experimental trials of the light boats on the Irwell.

* See Mr. Fairbairn's 'Remarks on Canal Steam Navigation.' 1831.



Digitized by Google

The Irish Canal boats were built at Birkenhead, and forwarded in sections to Ireland. About the same time, or shortly after, the 'Lord Dundas' and the 'Manchester' were introduced on the Forth and Clyde Canal, Messrs. Laird built the 'Alburka,' a small iron vessel, that went out to Africa with the Landers and Mr. Macgregor Laird, for the exploration of the Niger. The strength and sailing qualities of the whole of these vessels were confirmatory of the great superiority of iron over wood as a material for ship building; and we have only to refer to the extensive use and enormous increase that have taken place in its application, not only in this country but in every maritime state of the globe, to be convinced of the soundness of the principle, and the great superiority of the iron ship.

From the period to which we have alluded, and during the time of the working and experimental researches of the pioneers of iron ship building, we trace numerous improvements which have taken place from that time to the present. In the early stages of this important manufacture many difficulties had to be encountered, and it was only those who were the first to undertake the designs and labour of these constructions who were calculated to insure success, and competent to carry out the responsible duties consequent upon such undertakings. It was for that object that the author, who had resided in a large inland manufacturing town, removed that department of his establishment to Millwall, London, in order not only to carry out what appeared to him an entirely new and important principle of construction, but to prove that his previous researches were entitled to consideration, both on the part of the Government and those connected with the commercial enterprise of the country. It is not necessary to enumerate the opposition and competition that were raised against the establishment at Millwall, or to give special notice of the *innovators*, as they were called, who had the hardihood to make their appearances on the banks of the Thames as competitors to the great builders and shipwrights of the capital. Suffice it to observe that the establishment had to encounter opposition from every quarter, and after building upwards of one hundred vessels, some of them above 2,000 tons burden, the principal was under the necessity of retiring from an unequal contest; not, however, until

Digitized by Google

the great principle on which iron ships should be built had been established.

Since the author's retirement from iron ship building, as a department of his professional career, great and varied improvements have taken place in the construction of iron ships, and it has been clearly shown that vessels of large tonnage and great magnitude may be safely constructed of iron. For the extent to which this application has been carried we are indebted to the late Mr. Brunel, Mr. Scott Russell, of London, Messrs. Laird & Co., Mr. Vernon, of Liverpool, Mr. Robert Napier, and several other eminent builders of Glasgow. To the Clyde builders may be referred some of our most important constructions, and there is probably no part of the United Kingdom where greater energy and enterprise in this branch of industry is displayed.

It is evident that thirty years' practice in iron ship building must have improved the principle of construction, so as to render vessels of this material safer and better calculated to meet the requirements necessary for the navigation of dangerous and tempestuous seas. It is however clear that in some instances these results have not been attained, as numbers of vessels have been built and are now building of inferior material as well as defective in principle, thus impairing their security and rendering them unfit for service on the open sea. Much has yet to be done to rectify these mistakes, to raise the character of the iron ship builder, and ultimately to establish in the public mind perfect security in the strength of vessels of this description. We venture to hope that the time is not far distant when these desirable objects will be accomplished, and when it will become imperative on every builder to employ sound material and equally sound principles in the construction of these important structures.

With regard to ships of war, we make no apology for extracting from a work recently published by the author,* in which it is stated that 'the future destiny of nations seems to be involved in the consideration of iron, and its application to an entirely new system of construction in vessels of war, calculated to unite with equal facility the powers of attack and defence. To

* See Mr. Fairbairn, 'On Iron Manufacture,' Second Edition, 1865.

Digitized by Google

combine this force and power of resistance in one construction, is a desideratum not yet attained, but every effort is now being made by the Government of this and other maritime nations, to approximate as nearly as possible in the construction of ships of war to that desirable object. It appears from what has already been done by the Government of this country, and the preparations now going forward in the French dockyards, as also from the trials and experiments made in America, that the war ships and fleets of the future will undergo a thorough change, not only in form, but also in the material used in their construction. Thirty years' experience in the appliance of iron to the building of our mercantile navy, has shown the great superiority of that material for ship building; and much greater progress in this direction would have been made in the Government dockyards, but for two reasons—namely, the strong prejudices engendered against iron in the first instance, and the dangers arising from the effects of shot on iron ships in the second.

'As early as 1834–35, the Admiralty were urged to institute a series of experiments, to solve the difficulties which appeared to surround these opinions; but it required several years before their Lordships made up their minds as to what should be done. At last, through the influence of the late Admiral Sir George Cockburn, and others, the subject of iron ships was brought under consideration, and targets were ordered to be prepared at Woolwich, for experiment with a 32-pounder smooth-bore gun, at a range of only thirty yards. The result was condemnatory of the use of iron, and the Admiralty then fell back upon the old wooden walls, as the only class of vessels calculated for the purposes of war. This decision on the part of the Government retarded everything in the shape of progress, until the French Emperor, in 1855, gave a fresh impetus to the subject, by the introduction of thick iron plates for casing the sides of vessels, as a medium of resistance to projectiles at high velocities. This innovation—or invasion as it is now called—upon old constructions roused the lethargy into which we had fallen, and showed the weakness of our fleets and squadrons, when exposed to the attacks of "ironclads" of superior force, thoroughly protected by defensive armour. These facts, so

Digitized by Google

strikingly exemplified by the French iron-cased batteries during the Crimean war, could no longer be resisted, and hence followed the changes and experiments which are now in progress. It would be premature to conjecture what may be the ultimate results of those changes, as fortunately we are not engaged in war to enable us practically to test the efficiency of the vessels already built on the new principle; nor have we sufficient experience to enable the Admiralty to determine what size, form, and class of vessels are best adapted for a particular service. We are, however, feeling our way by experiment in the right direction, and we may safely predict a new and successful era in the construction of iron vessels, calculated to meet all the requirements of a powerful and effective navy.'

Digitized by Google

## CHAPTER II.

### ON THE STRAINS TO WHICH A SHIP IS SUBJECTED WHEN AFLOAT.

HAVING briefly noticed the origin and subsequent improvements that have taken place in iron ship building, it is important that the student of naval architecture should have all the information which a laborious life in this line of construction can supply. For this purpose it has been considered desirable to ascertain, from our previous knowledge and direct experimental research, data on which the naval architect can depend for the distribution and application of iron to those important structures, and moreover to equalise the parts in their respective resistances to strain. It would be presumptuous in us to imagine that we are qualified to communicate the knowledge of the true principle of form or the lines on which iron ships should be built. On the contrary, it is not our intention to assume any superiority in this respect, but simply to communicate to others what has taken much time and labour to learn, and which may be useful in directing attention to a subject on which the safety of the nation as a maritime power chiefly depends.

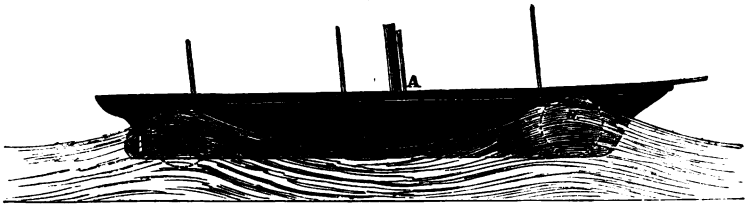
Before attempting to elucidate the practical principles which should be observed in the construction of iron ships, it seems requisite that we should first ascertain what are the natures and magnitudes of the strains to which ships are subjected when afloat.

1. Let us suppose a vessel in the middle of the Atlantic or Pacific Ocean having to encounter a rolling sea in a storm, where the elevation from the trough of the sea to the crest of the wave is 24 feet, and assuming the distance between them from point to point to be 380 to 400 feet; and again supposing that these waves move at a velocity of 10 knots an hour, and we have a large vessel supported—as represented in the diagram, fig. 1—by two waves, one at the bow and another at the stern, and her

Digitized by Google

midships partially unsupported, as if two liquid rollers *a a* (to use a familiar expression) were passing at the above rate under her bottom. In this position, the strains would have a tendency to crush the material composing the upper deck at A, and to tear

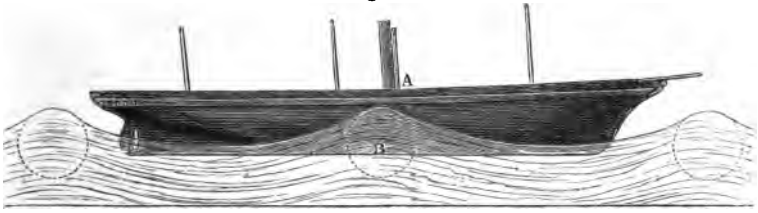
Fig. 1.




asunder the hull or bottom B. Hence the necessity for increased resistance in those parts.

2. Reversing this position, and supposing that our liquid rollers have passed from the bows and stern to the centre of

Fig. 2.




the ship, and we have her balanced in the shape of a scale-beam, as at fig. 2, with both ends unsupported. In this position the strains are reversed, and we have the crushing force

Fig. 3.

along the bottom, as at B, and the tensile force at A on the upper deck.

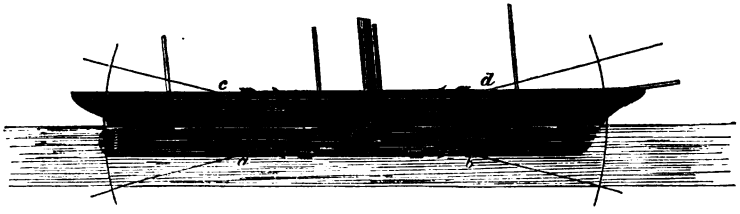
3. Assuming again that the waves, or liquid rollers, have

Digitized by Google

passed from the centre of the vessel half-way to the stern, and we again have the same forces continued, namely, tension on the upper deck at the point A, fig. 3, immediately over the apex of the surge, and compression at B, below.

4. In these forms we have nearly all the disturbances and variety of strains—independent of rolling—to which vessels are subjected when afloat. Under other circumstances, such as a vessel stranded on a lee shore, beaten on rocks or sandbanks, widely different forces come into operation, and the only safeguard in these positions is increased strength at midships, and a sufficient number of water-tight bulkheads to prevent her filling entirely with water. Let us take, for example, a vessel like the 'Warrior,' 380 feet long and 42 feet deep, as shown in fig. 4, and

Fig. 4.




treat it as a hollow beam floated or balanced on the fulcrum A as a centre, round which the two alternate forces revolve. In this position, every time that the vessel rises on the sea at the bow, the tensile strain is along the bottom, in the direction of the arrows *a*, *b*, whilst, at the same instant, the compression, or the tendency to crush it, is in the direction of the arrows *c*, *d*; and *vice versâ* as the bow of the ship descends in the opposite direction into the trough of the sea. Now, to guard against injury to the joints by these continued transfers of strain which surround the neutral axis A, it is essential to the security of the ship that there should be no slipping or movement on the joints, particularly at midships, where the strains are greatest on the bottom, and on the sides level with the upper deck.

5. Let us now state more explicitly what are the strains produced by inequalities of displacement or immersion, apart from the dynamic effect of a mass of water in a state of violent motion. When a vessel floats in still water, the weight of the displaced fluid is exactly equal to the weight of the floating

Digitized by Google

mass. In this case the plane of floatation is horizontal, and the downward pressure of the ship, acting through its centre of gravity, is directly opposed to and counteracted by the upward pressure of the displaced fluid acting through its centre of pressure; so that, under these circumstances, the material, in any section of the ship, undergoes no strain.* But when a ship sails in a rough sea, the line of floatation being no longer horizontal, she becomes subject to strains, due to this inequality of immersion, which vary with the circumstances under which they are produced.

6. When a vessel spans two crests of the waves, as represented in fig. 1, the extremities being more submerged than the middle, the upward pressure at each extremity is greater than it is at the middle, and, consequently, the material in a transverse section at this part must undergo a downward strain, due to this unbalanced pressure; in this case, therefore, the top part of the material in the transverse section undergoes a compressive strain. Now a precisely contrary action will take place under the following conditions.

* To find the displacement of a ship, the loaded draft being given:—Let the length of the ship, between the bend at the stern and the bend at the prow, be divided into any number of parts by equidistant transverse sections; put $a_1, a_2, \ldots a_n$ for the areas of these equidistant sections extending to the given line of draft, and $2d$ for their common distance apart; and moreover put $m_1, m_2, \ldots m_{n-1}$ for the areas of the middle or mean sections, taken in order; then the volume or content of any one of these $n$-1 portions may be approximately found by the prismoidal formula, and putting Q for the whole volume, we find

$$Q = \frac{d}{3}\left\{a_1 + a_n + 4(m_1 + m_2 + \ldots + m_{n-1}) + 2(a_2 + a_3 + \ldots + d_{n-1})\right\}$$

The areas, $a_1$, $a_2$, &c., of the different sections may be found from a similar formula:

Thus, let the surface of any section be divided into any *even* number of equidistant ordinates or perpendiculars, say 6; put $p_1, p_2, \ldots p_7$, for these equidistant ordinates, and $k$ for their common distance apart, then the area of the section will be approximately expressed by the formula,

$$\frac{k}{3}\left\{p_1 + p_7 + 4(p_2 + p_4 + p_6) + 2(p_3 + p_5)\right\}$$

The volumes of the portions at the extremities may be found in the same manner: putting $q$ for the volume of this portion at the stern, $q_1$ for that at the prow; moreover putting $w$ for the weight of a cubic foot of the water, all the dimensions being in units of feet, and W for the weight of the displacement in tons:

$$W = \frac{w}{2240}(Q + q + q_1).$$

Digitized by Google

7. When the ship is supported on the crest of a wave, as represented in fig. 2, the water at the extremities is below the line of floatation, whilst the water at the centre is above it, and the buoyancy of the water at the centre is then greater than it is at the extremities; hence it follows that the extremities must be bent downwards with force due to this unbalanced pressure, that is, the top part of the material in the transverse section at the centre undergoes a tensile strain.

8. When the ship advances on a wave, as represented in fig. 3, the head of the ship, being more submerged than the stern, will be elevated by the additional buoyancy of the water at that part, and the upward pressure at this part will be greater than the downward pressure of the load over it; hence the unbalanced downward pressure of the load towards the stern produces a tensile strain on the top part of the material in the transverse section at the centre. This strain, no doubt, may be intensified when the ship runs ahead against a wave driven on by a violent gale of wind.

9. Dr. Rankine has investigated this question, and in a paper read before the Mechanical Section of the British Association for the Advancement of Science, entitled 'On some of the Strains of Ships,' he states that 'in previous scientific investigations respecting the strains which ships have to bear it has been usual to suppose the ship balanced on a point of rock, or supported at the ends on two rocks. The strains which would thus be produced are far more severe than any which have to be borne by a ship afloat.' The author computes the most severe straining action which can act on a ship afloat—viz. that which takes place when she is supported midships on a wave crest, and dry at the ends—and he finds that the bending action cannot exceed that due to the weight of a ship with a leverage of one-twentieth of her length, and the racking action cannot exceed about sixteen one-hundredths of her weight.* Applying those results to two remarkably good examples of ships of 2,680 tons displacement, one of iron and the other of wood—described by Mr. John Vernon, in a paper read to the Institution of Mecha-

* The greatest bending moment when a ship is balanced on the crest of a wave $= \frac{\text{displacement} \times \text{length}}{20}$.

Digitized by Google

nical Engineers, in 1863—he finds the following values of the greatest stress of different kinds exerted on the material of the ship:—'In the iron ship, tension 3·98 tons per square inch; thrust 2·35; racking stress 0·975. It follows that in the iron ship the factor against bending is between 5 and 6, agreeing exactly with the best practice of engineers, and that there is a great surplus of strength against racking. In the wooden ship, tension 0·375 tons per square inch; thrust 0·293. Here the factor of safety is between 10 and 15, which is also agreeable to good practice in carpentry. As for the racking action, the iron diagonal braces required by Lloyd's rules would be sufficient to bear one-third of it only, leaving the rest to be borne by the friction and adhesion of the planking.'

10. The maximum strain of a ship afloat appears to take place when she is supported on the crest of a wave, as represented in fig. 2. Dr. Rankine has determined this strain to be about one-fifth of the ultimate strength of the material. Now it must be borne in mind that this apparently small strain on the material may assume the form of a destructive force when it is alternately laid on and taken off for an indefinite number of times, especially when it is considered that these strains are first in one direction and then in another; that is to say, the material in the top section (the weakest part of the section) is at one time in a state of tension and at another time in a state of compression.

11. On this very important question of alternate strains we are fortunate in having before us a laborious series of experiments on the endurance of iron-jointed beams subjected to these changes; not exactly similar to that of a steam-engine beam, but a less severe test arising from alternately imposing and reimposing the load in the same direction. This, it will be observed, was simply a constant change of tensile force in one direction and compression on the other, whereas that of a ship is subject to both tension and compression on the bottom and upper deck as she rises and falls upon the waves of the sea.

On referring to the experiments to which we have alluded, we arrive at this curious and interesting fact, that the joints of an iron riveted beam sustained upwards of 3,000,000 changes of one-fourth the weight that would break it without any apparent

Digitized by Google

injury to its ultimate powers of resistance. It, however, broke with 313,000 additional changes when loaded to one-third the breaking weight, evidently showing that the construction is not safe when tested with alternate changes of a load equivalent to one-third the weight that would break it.*

These results are probably not without interest as regards the construction of iron vessels, as they appear to be conclusive that time is an element in the endurance of structures when subjected to severe strains affecting their ultimate powers of resistance. It is difficult to determine or pronounce what is the correct measure of safety, whether one-fifth or one-fourth the breaking weight; but we have sufficient data to be assured that every disturbance, however minute, in the molecular construction of bodies finally tends to destruction, and it is only a question of time when rupture ensues. We may, however, be assured that a ship, as well as a beam, is practically safe when the strains repeated in the same direction do not exceed the government rule of five tons per square inch upon the wrought-iron plates of which it is composed.

12. These results are highly satisfactory so far as they profess to go; but, in the absence of reliable *direct* experiments, it seems highly probable that a strain of 5 tons per square inch on the material, acting alternately in opposite directions, would at least injure, if it did not fracture, the material after a great number of alternations. Such a number of alternations might not take place during the continuance of a single storm, but the destructive effect goes on accumulating in the course of years. Hence it is highly desirable that iron ships should be built much stronger than they are at present.

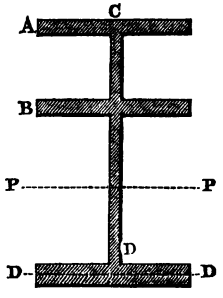
13. It will be readily understood that the tensile strain of 4 tons per square inch, determined by Dr. Rankine as the maximum strain which a ship undergoes when afloat, has a relation to the amount, as well as to the distribution, of the material in the transverse section of the ship. Now the ship, upon which these calculations were based, is decidedly defective as regards the distribution of the material. If the section of the material in the upper deck were increased by 100 square inches, other things remaining the same, the maximum strain per square inch

* Vide 'Philosophical Transactions,' 1864.

Digitized by Google

would be reduced to 3 tons per square inch, or about one-seventh of the ultimate strength of the iron. With this increase of strength such a vessel would probably survive the destructive action of a thousand storms.* Were it practicable, the upper section might be still further increased with advantage.

Fig. 5.




* Let A D represent a transverse section of the material in the ship, where the material in the section is supposed to be condensed into three flanges and a central rib;

A the section of the iron in the upper-deck;

B the section in the lower-deck;

D the equivalent section in the bottom; and

C D the equivalent section of the two sides of the ship.

Let W = the displacement = 2700 tons;

$l$ = the length of the ship, = $92\frac{1}{2} \times 2$ = 185 feet;

M = the greatest bending moment when balanced on the crest of a wave $= \frac{W \times l}{20} = 24975$.

$a$ = 213 square inches, the section of the material in A; $g$ = A P, the distance of its centre of gravity from the neutral axis P P.

$h$ = the distance of the upper edge of A from the neutral axis, S being put for the resistance of tension per square inch of the material at this edge.

$b$ = 55 square inches, the section B; $g$ = the distance of its centre of gravity from P P.

$a_1$ = 493 square inches, the section D; $g_1$ = D P, the distance of its centre of gravity from P P.

$h_1$ = the distance of the lower edge of D from P P; $S_1$ being put for the resistance of compression per square inch of the material at this edge.

$k_0$ = 440 square inches, the section of the rib C D, extending from the centre of A to that of D, and having a section of 18 square inches per lineal foot.

$k$ = the area of the rib above P P, $k_1$ = the area of the rib below P P.

$d$ = A D = $23\frac{1}{2}$ feet, the distance between the centres of gravity of A and D; $d_1$ = B D = 16 feet, the distance between the centres of gravity of B and D.

$I_0$ = the moment of inertia of the whole section.

Now, assuming for wrought iron that the amount of compression is equal to that of elongation under the same force, it follows that the neutral axis P P will pass through the centre of gravity of the section. Taking D D therefore as an axis of moments, we get

$$g_1 = \frac{(a + \frac{1}{2} k_0)\ d + b.d_1}{a + b + k_0 + a_1} \quad \ldots (1)$$

Substituting the values of these symbols, as above given, we find, $g_1 = 9\frac{1}{4}$, and $\therefore g = 23\frac{1}{2} - 9\frac{1}{4} = 14\frac{1}{4}$. But, in this case, $h = g$, and $h_1 = g_1$, very nearly;

$\therefore h = 14\frac{1}{4}$, and $h_1 = 9\frac{1}{4}$, very nearly.

Digitized by Google

14. When a ship is stranded, the strains to which she is subjected (besides the destructive action of the waves) depend upon the position of the points of support. When she is supported at the extremities, and hollow in the middle, the moment, M, of the weight of the ship to produce transverse fracture at the centre is expressed by the equality

$$M = \tfrac{1}{2} W . G \ldots (1),$$

where W represents the weight of the whole ship and cargo, and G the distance of the centre of gravity of each half of the ship from either of the points of support.

When the ship is supported at a point in the centre, $l$ being put for the length of the ship, this equality becomes,—

$$M = \tfrac{1}{2} W \left(\tfrac{1}{2} l - G\right) \ldots (2).$$

When the load is uniformly distributed throughout the length of the ship, $G = \frac{1}{4} l$, then these equalities respectively become,—

$$M = \tfrac{1}{8} W l,$$

that is, the moments tending to produce fracture, in the two cases, are equal.

15. But a ship is always more loaded at midship than towards the extremities; hence it is that the strain of the load on the centre transverse section is much greater in the former than in the latter case, that is, the value of M derived from eq. (1) is always greater than that derived from eq. (2). For example, suppose a ship of 2,800 tons, and 200 feet length, to be divided into six parts of equal length, three on one side of the centre

Now the moment of the resistance of the material to fracture is expressed by $\frac{s}{h} \cdot I_0$, or by $\frac{s_1}{h_1} \cdot I_0$;

$$\therefore M = \frac{s}{h} \cdot I_0 \text{ or } \frac{s_1}{h_1} \cdot I_0;$$

$$\therefore s = \frac{h \cdot M}{I_0}, \text{ and } s_1 = \frac{h_1 \cdot M}{I_0};$$

Where $I_0 = (a + \frac{1}{3} k) h^2 + (a_1 + \frac{1}{3} k_1) h_1^2 + b \cdot q^2$, very nearly.

Whence we find $I_0 = 113480$, $s = 3{\cdot}1$, and $s_1 = 2{\cdot}03$; that is, the strain in question produces a tensile strain of about 3 tons per square inch on the material in the upper edge of the section, and a compressive strain of about 2 tons per square inch on the material in the lower edge of the section. In the former case, the strain is about one-seventh the ultimate tensile strength of wrought iron, and in the latter case it is about one-eighth of the ultimate compressive strength.

Digitized by Google

and three on the other, and suppose the respective weights of these parts, proceeding from the centre to either extremity, to be in order, 600, 500, and 300 tons; then the value of G, in this case, will be 58 feet; and from formula (1) we find,—

$$M = \tfrac{1}{2}W G = \tfrac{1}{2} \times 2{,}800 \times 58 = 81{,}200,$$

and from formula (2) we find

$$M = \tfrac{1}{2}W(\tfrac{1}{2}l - G) = \tfrac{1}{2} \times 2{,}800 \times 42 = 58{,}800.$$

Hence it appears that the strain, tending to fracture the ship at the centre, in the latter case is less than three-fourths of what it is in the former case.

If the load had been uniformly distributed along the length of the vessel, then $G = \frac{1}{4}l$, and in both cases,

$$M = \tfrac{1}{8}W.l = \tfrac{1}{8} \times 2{,}800 \times 200 = 70{,}000.$$

Thus it appears that the extra load towards the centre of the ship increases the strain, tending to produce transverse fracture at the centre in the first case, but diminishes this strain in the latter case.

Hence also it appears that the greatest strain on a ship takes place when she is supported at the extremities on some hard or unyielding substance.

The custom of distributing the load more towards the centre than towards the extremities of the ship is highly judicious, inasmuch as it reduces considerably the strain produced on the transverse section when the ship is balanced on the crest of a wave.



Digitized by Google

## CHAPTER III.

### ON THE PROPERTIES OF IRON CONSIDERED AS A MATERIAL FOR SHIP BUILDING, AND THE RESISTANCE OF IRON PLATES TO THE FORCE OF EXTENSION.

1. WROUGHT IRON, employed as a material for the construction of ships, possesses advantages over every other kind of material. Besides other advantages, it possesses great strength, durability, and lightness; it may be hammered into any requisite shape, and one piece may be securely united to another by welding or by riveting, so that comparatively small pieces may be so united and combined as to form the strongest and most ponderous ship.

With these preliminary observations we now proceed to discuss the important question of iron and its various modes of application to the construction of vessels of every grade and dimension, in the war as well as in the mercantile navies of the country.

On this very important inquiry we have to direct attention to the following divisions of the subject:—

1st. On the properties of iron considered as a material for ship building. Considered in Chapters III. and IV.

2nd. On the distribution of the material of wrought-iron plates and frames as applied to the construction of iron ships. Considered in Chap. V.

3rd. Combinations of iron and wood. Considered in Chap. VI.

4th. On the varied forms of construction of ships of war. Considered in Chap. VII.

5th. On the properties of cast and wrought iron and steel as materials for the construction of ordnance. Considered in Chap. VIII.

6th. On the properties of iron armour plates and their resistance to projectiles at high velocities. Considered in Chap. IX.

7th. On the impact and resistance of shot and shell fired against iron armour plates. Considered in Chap. X.

Digitized by Google

8th. On the practical construction of iron ships. Considered in Chaps. XI. and XII.

9th. On the comparative merits of ships of war. Considered in Chap. XIII.

10th. On the strength of material, theoretically and practically treated, in relation to the construction of iron ships. Considered in Chap. XIV.

## ON THE PROPERTIES OF IRON CONSIDERED AS A MATERIAL FOR SHIP BUILDING.

2. Iron is found in combination with various substances, and widely diffused in certain definite proportions throughout the animal and vegetable kingdom, and it is imbedded and stratified in great abundance in every formation of the earth's crust. It occurs in the crystalline and arenaceous form, lying deep in strata, filling veins and faults in rock-formations to a great extent, and in some cases it is scattered in great profusion over the surface of the ground. There are great varieties of iron ores—such as the magnetic oxides, which yield about 72 per cent. of iron; the specular or red hæmatite; the peroxide of iron, containing 70 per cent.; and the carbonate or spathic ore, which occurs in a mixed state with large quantities of argillaceous, carbonaceous, and siliceous substances forming large deposits of spathic ore, clay ironstone, and black bands, from which most of the iron of this country is obtained, and to which our observations chiefly apply as the material we have to deal with for the construction of iron ships.

3. Iron, as it flows from the smelting furnaces, assumes the crystalline form when cooled and run into ingots or pigs. In this state it is remelted and decarbonised in the puddling furnace, formed into blooms, hammered, re-heated and rolled into bars and plates. In this state the ship builder receives it in the form of plates, angle iron, and T iron, and to these forms it will be necessary to direct attention in order that a clear conception may be had of the strength and other properties of the material of which the structure is composed. For this purpose we have to refer to a class of experiments made some years since, and published in the 'Philosophical Transactions,'* entitled

* 'Philosophical Transactions,' Part II. 1850.



Digitized by Google

'An Experimental Inquiry into the Strength of Wrought-Iron Plates and their Riveted Joints as applied to Ship building and Vessels exposed to severe Strains.'

4. Iron in its malleable state, like other metals, becomes ductile and capable of being extended by drawing, while its thickness or diameter is diminished without the risk of fracture or separation of its parts. It may be drawn in the direction of its fibre to an enormous extent, and, converted into steel, it is capable of being extended until it becomes almost as fine as the human hair. The order of ductility of the metals is gold, silver, platinum, iron, copper, zinc, tin, lead, nickel, palladium, &c. Gold in particular is so exceedingly plastic in character that it has been known to be drawn to the $\frac{1}{500}$ part of an inch in diameter.

### PROPERTY OF TENACITY.

5. To arrive at the stability, strength, and other properties of a structure, when united and composed of parts of the same material or in combination with any other material, it is essential that we should make ourselves thoroughly acquainted with its endurance, powers of resistance, flexibility, elasticity, and such other properties as may be called into action by forces to which it is exposed. Without this knowledge, the different parts of every construction, instead of being duly proportioned to the strains each has to bear, are left to chance as regards position, and take their places according to the views, probably the ignorance or caprice, of the builder. In every construction, but more especially in that of a ship, it is necessary, in the first instance, to determine the position and direction of the strains to which it may be subjected; and, in the second place, to prepare to meet those strains by the selection and position of the material, so as to determine the best mode of construction. Having attained that object, the knowledge previously acquired will be found highly valuable as an assistant to the architect and ship builder in the formation of his structure and the selection of his material; and, moreover, it will enable him to place it where strength is required, and where it is calculated to offer, in conjunction with its associated parts, a maximum power of resistance.

6. To facilitate these operations, and for the guidance of the

Digitized by Google

naval architect, we have to direct attention to the following experimental facts, viz.:—

1st. The strength of plates when torn asunder by a direct tensile strain in the direction of the fibre, and when torn asunder across it.

2ndly. On the ductility, elongation, and dynamic resistance of wrought iron.

3rdly. On the strength of the joints of plates when united by rivets, as compared with the plates themselves.

I. Punching.
II. Riveting,
III. Rivets.

And lastly. On the resistance of plates to the force of compression.

7. On the first of these subjects, where the iron plates were torn asunder in the direction of the fibre and across it, the following results were obtained:—

TABLE I.

| Description of Plates | Mean Breaking Weight in the Direction of the Fibre, in Tons per Square Inch | Mean Breaking Weight across the Fibre, in Tons per Square Inch |
|---|---|---|
| Yorkshire plates . . | 25·770 | 27·490 |
| Yorkshire plates . . | 22·760 | 26·037 |
| Derbyshire plates . . | 21·680 | 18·650 |
| Shropshire plates . . | 22·826 | 22·000 |
| Staffordshire plates . . | 19·563 | 21·010 |
| Mean . | 22·519 | 23·037 |

8. From the above it will be observed that the average strength of plates is about 22½ tons to the square inch, the maximum being in favour of the Yorkshire plates, and the minimum those of Staffordshire. It will be noticed that a slight difference exists between the plates drawn asunder in the direction of the fibre, and those drawn across it; that the aggregate of strength is only about $\frac{1}{40}$ in favour of that torn asunder across the fibre, the difference of resistance being due to the anomalous condition of the Yorkshire plates, which gives a higher value to the iron in that direction, contrary to what, in general practice, is the fact.

9. It would probably be unfair, therefore, to class plates with

Digitized by Google

bar iron of the same quality, as bar iron is much more elongated and drawn into fibre in passing through the rolls than the same material when rolled into plates. We may, however, compare plates with the bars experimented upon by the late Mr. Telford, who found (in his experiments to determine the strengths of different irons, previous to his construction of the Menai Suspension Bridge) that out of nine faggoted specimens, selected from the Swedish, Welsh, and Staffordshire irons, he obtained a tenacity of 29·25 tons to the square inch.

| | | | |
|---|---|---|---|
| Captain Brown's experiments for the same purpose gave . . . | 25·00 | tons per | square inch |
| Minord and Desames' . . . | 25·00 | „ | „ |
| Yorkshire plates experiments . . | 24·50 | „ | „ |
| Shropshire plates „ . . | 22·82 | „ | „ |
| Derbyshire plates „ . . | 21·68 | „ | „ |
| Staffordshire plates „ . . | 20·32 | „ | „ |
| Giving a mean tenacity for plates of | 23·22 | „ | „ |

Comparing this with the strength of bar iron from the best material, and making allowance for the latter having been worked, rolled, and drawn into fibre, the difference in strength is not so great as might have been expected, being in the ratio of 29 : 23 or 1 : ·8 nearly.

10. Plates of ordinary manufacture, or such as are used in ship building, seldom exceed in tenacity 20 tons to the square inch. Unfortunately, many of them are under that standard, but no plate should be allowed, on any account, to enter into the construction of a sea-going vessel under a tensile strain of 20 to 22 tons per square inch. Small vessels, such as boats for canals and rivers, may venture upon an inferior standard of quality, but, even with this allowance, there is no economy in the use of a material which is neither safe nor durable.

### PROPERTIES OF DUCTILITY, ELONGATION, ETC.

11. We have already noticed that ductility is a property highly valuable in iron, and, we may add, when combined with tenacity it becomes still more valuable; in fact, ductility is, for practical purposes, the true measure of its strength and practical utility. These properties being of great importance in the manufacture of iron, it may be useful to give a few examples,

Digitized by Google

derived from recent experiments, illustrating the principle on which it is supposed that good iron yields and becomes attenuated, when acted upon by forces which draw it longitudinally in the direction of the fibre.

It has been stated that iron, like most other metals, is of a ductile character. In this respect, however, it is inferior to gold, silver, and platinum; but it is in advance of copper, zinc, and tin, and may be considered superior to any of these metals, on account of its tenacity and strength; and from this we derive its adaptation to the arts of construction and its value as an article of commerce. Iron is therefore of inestimable value, and, combined with properties such as those enumerated above, it becomes one of the most important and useful of metals.

12. The following experimental results were derived from seven different thicknesses of iron plates, manufactured by four different firms, and marked A, B, C, and D:—

A. Six specimens of iron plates.

B. Seven specimens of iron plates.

C. Seven specimens—homogeneous metal.

D. Seven specimens—rolled iron.

The whole of these specimens were torn asunder by a tensile strain, and recorded in the following summary:—

TABLE II.—SUMMARY, GIVING MEAN TENSILE STRENGTH OF EACH SERIES OF PLATES, OR STATICAL BREAKING STRAIN.

| Approximate Thickness of the Plates in Inches | Tensile Breaking Weight per Square Inch of Section | | | | Mean of Plates of the same Thickness Tons |
|---|---|---|---|---|---|
| | A Plates Tons | B Plates Tons | C Plates Tons | D Plates Tons | |
| ¼ inch . | 24·344 | 24·167 | 30·703 | 17·470 | 24·171 |
| ½ inch . | 25·750 | 23·220 | 33·694 | 11·055 | 23·430 |
| ¾ inch . | ... | 29·432 | 30·913 | 26·473 | |
| 1½ inch . | 24·158 | 22·299 | 26·197 | 25·158 | 24·453 |
| 2 inches . | 25·348 | 23·657 | 27·038 | 24·634 | 25·169 |
| 2½ inches . | 24·110 | 23·921 | 27·506 | 22·732 | 24·569 |
| 3 inches . | 25·039 | 23·540 | 27·386 | 24·159 | 25·031 |
| Mean of thin plates | 25·047 | 25·606 | 31·770 | 18·333 | |
| Mean of thick plates | 24·644 | 23·354 | 27·032 | 24·171 | |
| Mean of all of one make . | 24·792 | 24·319 | 29·063 | 21·669 | |

Digitized by Google

The order of merit in the thinner plates is—(1) C; (2) B; (3) A; (4) D. With thicker plates it is—(1) C; (2) A; (3) D; (4) B. The mean of the whole gives—(1) C; (2) A; (3) B; (4) D.

13. The homogeneous metal plates exhibit throughout the highest tenacity, but decrease in their powers of resistance as the plates are made thicker. Of the iron plates, those marked A are most uniform in strength, the extreme difference being 1·64 tons; the B plates vary to the extent of 7·133 tons; and the D plates 14·103 tons. But the quarter and half inch plates of the latter series would appear to have been burnt or injured in the manufacture.

14. Taking the means given in the last column, it will be seen that in the average there is no great difference between the thicker and the thinner plates. The extreme variation is only 1·74 or $1\frac{3}{4}$ tons. If we compare these means with the corresponding mean densities, there is a uniform correspondence; thus—

| | | | |
|---|---|---|---|
| $1\frac{1}{2}$ inch Plates . . | 7·7471 | Density | 24·453 Tenacity |
| 2 inch Plates . . | 7·7684 | „ | 25·169 „ |
| $2\frac{1}{2}$ inch Plates . . | 7·7660 | „ | 24·569 „ |
| 3 inch Plates . . | 7·7666 | „ | 25·031 „ |

Here the density and tenacity increase and diminish together and the same correspondence will be found, generally speaking, in each individual case, on comparing the two tables; but there are exceptions in the case of the D plates. Taking into account the fact that the specimen employed in obtaining the specific gravity was cut at a distance of about ten inches from the part broken by tension, the coincidence is sufficiently striking. The comparison also holds good, if we take the means of plates of the same manufacture, with one exception.

| | | | |
|---|---|---|---|
| A Plates . . | 7·8083 | Density | 24·644 Tenacity |
| B Plates . . | 7·7035 | „ | 23·354 „ |
| C Plates . . | 7·9042 | „ | 27·032 „ |
| D Plates . . | 7·6322 | „ | 24·171 „ |

15. In Table III. the order in which the different series of plates stand with reference to ultimate elongation nearly coincides with the order in which they stand in reference to tenacity, when the means of plates of the same manufacture are compared.

Digitized by Google

On the other hand, if we compare the means of plates of the same thickness, we find that, on the whole, the ultimate elongation increases as the plates become thicker, while no law of this kind could be perceived when the mean tenacities were taken.

TABLE III.—SUMMARY, GIVING THE ULTIMATE ELONGATION PER UNIT OF LENGTH.

| Approximate Thickness of the Plates in Inches | Ultimate Elongation per Unit of Length | | | | Means of Plates of the same Thickness |
|---|---|---|---|---|---|
| | A Plates | B Plates | C Plates | D Plates | |
| ¼ inch . . | ·0620 | ·0300 | ·2560 | ·0080 | 0·0890 |
| ½ inch . . | ·0760 | ·0400 | ·1000 | ·0111 | 0·0568 |
| ¾ inch . . | ... | ·1000 | ·2080 | ·0400 | 0·1160 |
| 1½ inch . . | ·1763 | ·1462 | ·1925 | ·1925 | 0·1769 |
| 2 inches . . | ·3050 | ·2525 | ·3450 | ·1788 | 0·2703 |
| 2½ inches . . | ·2880 | ·3200 | ·2950 | ·1600 | 0·2658 |
| 3 inches . . | ·3200 | ·2650 | ·2575 | ·2333 | 0·2689 |
| Mean of thinner plates | ·0690 | ·0566 | ·1880 | ·0197 | |
| Mean of thicker plates | ·2723 | ·2459 | ·2725 | ·1913 | |
| Mean of all the plates | ·2046 | ·1650 | ·2363 | ·1176 | |

16. Mr. Mallet has introduced from Tredgold a new co-efficient of strength, called the 'modulus of resilience,' of considerable importance in these inquiries. This co-efficient gives the dynamic resistance to rupture, or foot pounds of work done in rupturing the material. This may be estimated with sufficient accuracy by multiplying the breaking weight in pounds by half the ultimate elongation.

17. It will be noticed that the numbers given in the case of the thinner plates are very variable, in consequence of the great fluctuations in the value of the ultimate elongation in those plates. This irregularity would have been eliminated if several specimens of each had been tried; or, still better, if the specimens had been so long that the elongation of a much

Digitized by Google

greater extent of metal could have been ascertained. The results obtained in the case of the thicker plates, with precisely similar round bars, are more uniform.

18. Bearing this in mind, the table exhibits several remarkable results. First, taking the means of plates of the same

TABLE IV.—MR. MALLET'S CO-EFFICIENT, OR WORK DONE IN CAUSING RUPTURE, CORRESPONDING WITH RESISTANCE TO IMPACT.

| Approximate Thickness of Plates | Foot Pounds of Work causing Rupture | | | | Mean of Plates of the same Thickness |
|---|---|---|---|---|---|
| | A Plates | B Plates | C Plates | D Plates | |
| ¼ inch . . | 1690·5 | 812·0 | 8802·7 | 156·5 | 2865·4 |
| ½ inch . . | 2191·8 | 1040·2 | 3773·7 | 137·4 | 1785·8 |
| ¾ inch . . | ... | 3296·5 | 7201·5 | 1186·0 | 3895·0 |
| 1½ inch . . | 4767·5 | 3651·3 | 5648·0 | 5424·0 | 4872·7 |
| 2 inches . . | 8659·0 | 6690·2 | 10448·0 | 4933·1 | 7682·6 |
| 2½ inches . . | 7776·8 | 8573·4 | 9087·2 | 4073·7 | 7377·7 |
| 3 inches . . | 8973·7 | 6987·0 | 7878·0 | 6312·7 | 7787·8 |
| Mean of thinner plates | 1941·1 | 1716·2 | 6592·6 | 493·3 | |
| Mean of thicker plates | 7544·2 | 6475·5 | 8265·3 | 5185·9 | |
| Mean of plates of same make | 5676·6 | 4435·8 | 8806·5 | 3174·8 | |

thickness, it appears that the dynamic resistance increases progressively as the plates increase in thickness; in fact, the thick plates exhibit two and a half times the resistance of the thinner ones. The only exception to this general law is the quarter-inch homogeneous metal plate, which was extremely ductile.

19. Then, in the next place, it is to be observed that the dynamic resistance increases with the thickness of the plates in a higher ratio in the iron plates than in the homogeneous metal plates; thus—

Digitized by Google

TABLE V.

| Description of Plates | Thinner Plates | Thicker Plates | Ratio |
|---|---|---|---|
| | Foot Pounds | Foot Pounds | |
| A Plates } Iron | 1941·1 | 7544·2 | 1 to 3·89 |
| B Plates } Iron | 1716·2 | 6475·5 | 1 to 3·77 |
| D Plates } Iron | 493·3 | 5185·9 | 1 to 10·52 |
| C Plates Steel | 6592·6 | 8265·3 | 1 to 1·25 |

20. The result of this is, that the superiority of the homogeneous metal to iron is very striking in the thin plates, but becomes less and less as the plates increase in thickness. Thus, taking the best of the iron plates—namely, series A—for comparison, we have the following ratios between the iron and steel:—

TABLE VI.

| Thickness in Inches | A Plates Foot Pounds | C Plates Foot Pounds | Ratio of Dynamic Resistance |
|---|---|---|---|
| ¼ inch | 1690·5 | 8202·7 | 1 to 5·21 |
| ½ inch | 2191·8 | 3773·7 | 1 to 1·72 |
| ¾ inch | ... | 7201·5 | |
| 1½ inch | 4767·5 | 5648·0 | 1 to 1·19 |
| 2 inches | 8659·0 | 10448·0 | 1 to 1·20 |
| 2½ inches | 7776·8 | 9087·2 | 1 to 1·17 |
| 3 inches | 8973·7 | 7878·0 | 1 to 0·88 |

21. In Table VI. we see that the ratio decreases progressively with great regularity, from 1 : 5·21 to 1 : 0·88; that is, the work done in rupturing the ¼-inch plates is five times as great in homogeneous metal as in wrought iron; but the superiority decreases as the metal increases in thickness, as in the 3-inch plates the resistance of the iron is 12 per cent. greater than that of the homogeneous metal. These results correspond with those obtained in the trials with ordnance.* Thus, if we take the mean between the thinnest plate which resisted shot of a given weight, fired with the ordinary service charge of ⅛th of the weight of the shot of powder, and the thickest which was

* See Mr. Fairbairn's 'Experimental Researches. First Report of the Special Committee on Iron,' page 15.

Digitized by Google

penetrated by it, as the maximum thickness of penetration with the projectile, we have, from the experiments at Shoeburyness, the following results:—

TABLE VII.

| Rifled Gun | Weight of Projectile in lbs. | Least Thickness which would resist the Shot in Inches | | Ratio of Resistance of Plates of equal Thickness |
|---|---|---|---|---|
| | | A Plates | C Plates | |
| Wall piece . . | 0·344 | 0·87 | 0·62 | 1 : 1·97 |
| Armstrong gun . | 6·25 | 1·25 | 1·15 | 1 : 1·18 |
| ,, | 11·56 | 1·75 | 1·75 | 1 : 1·00 |
| ,, | 24·81 | 2·25 | 2·50 | 1 : 0·81 |

22. The results in this table are only roughly approximate; but they show a decreasing resistance in the C plates, when compared with the A plates.

The results in the last column strikingly correspond with those in the preceding table, if plates of the same thickness be compared.

On comparing Table IV., giving Mallet's co-efficient, with the specific gravities, similar correspondence is observable to that already noticed in the case of a tensile breaking strain. The exceptions also occur in the same series, namely, the D plates.

Of the iron plates of different manufacturers, the A series throughout manifests the greatest amount of dynamic resistance; next to it the hammered plates of series B; and, lastly, the rolled plates of series D.

23. Taking the thicker plates, which give the most accurate results, and employing the iron plates of series A as a standard of comparison, we have the following ratios of dynamic resistance:—

| | |
|---|---|
| A Plates . . . | 1000 |
| B Plates . . . | 858 |
| C Plates . . . | 1095 |
| D Plates . . . | 688 |

the maximum difference amounting to 41 per cent. between C and D, and 31 per cent. between A and D.

24. The fracture of the iron plates in all the trials was of

Digitized by Google

the dull grey laminated structure, except in the case of D, 3 inches thick, and B, 3 inches thick. These were more or less crystalline, but they were of average tenacity and more than average ductility, so far as that is indicated by the ultimate elongation. The homogeneous metal plates had a much brighter and closer texture, which might be described as finely granular in the 3-inch plate, and coarsely granular in the $2\frac{1}{2}$-inch plate. The others were finely laminated.

25. With regard to the ultimate elongations given in Table III., the following additional observations may be made. Comparing the elongations of plates of the same make, we find the steel giving the greatest elongation, namely, 0·2725 per unit of length in the thicker plates. But the A plates of iron are almost identical, namely 0·2723. Next, the B plates give 0·2459; and lastly, very much lower, the D plates give 0·1913. In the steel plates the maximum elongation is given by the 2-inch plates; in series A by the 3-inch plates; in series B by the $2\frac{1}{2}$-inch plates; and in series D by the 3-inch plates. That the iron plates give an elongation, which increases with the thickness of the plates, will be evident from the following numbers, which are the means of the elongations of the three series of iron plates:—

| Thickness of Plates in Inches | Mean ultimate Elongation of Plates A, B, and D, per Unit of Length | Differences |
|---|---|---|
| $\frac{1}{4}$ | 0·0333 | |
| $\frac{1}{2}$ | 0·0427 | ·0094 |
| $\frac{3}{4}$ | 0·0700 | ·0273 |
| $1\frac{1}{2}$ | 0·1717 | ·1017 |
| 2 | 0·2428 | ·0711 |
| $2\frac{1}{2}$ | 0·2560 | ·0132 |
| 3 | 0·2728 | ·0168 |

26. The relative amount of ultimate elongation in the thicker plates, taking the Low Moor plates of series A as the standard, is:—

| | | | |
|---|---|---|---|
| A Plates | Iron | | 1·000 |
| B Plates | Iron | | 0·902 |
| D Plates | Iron | | 0·702 |
| C Plates | Steel | | 1·000 |

In these researches it will be observed that, assuming the

Digitized by Google

amount of elongation to be the measure of ductility, the A plates from Low Moor, and the C, steel, plates are on the average identically the same as regards the softness of the material. But in the 3-inch plates the iron is very superior to the steel.'

27. To the above extract from the Report of the Special Committee on Iron may be added the results of some experiments on the tensile strength of S C bars, conducted some years since at Woolwich by Mr. Loyd, Inspector of Machinery. 'To that gentleman we are indebted for the following results:—

TABLE VIII.—SUMMARY OF RESULTS, TENSILE STRENGTH OF BARS.

| Length of Bar in Inches | Diameter of Bar in Inches | Breaking Weight in Tons | Elongation in Inches | Elongation per Unit of Length |
|---|---|---|---|---|
| 120 | 1·375 | 32·21 | 26·0 | ·216 |
| 42 | 1 375 | 32·125 | 9·8 | ·233 |
| 36 | 1·375 | 32·35 | 8·8 | ·244 |
| 24 | 1·375 | 32·00 | 6·2 | ·258 |
| 10 | 1·375 | 32·29 | 4·2 | ·420 |

28. In another series of experiments it was found that the continued strain of three-fourths of the breaking weight had no effect upon the bars, and that it might have been prolonged indefinitely without injury to the cohesive force by which the particles were united. These facts, although exceedingly interesting at the time, have since been carefully investigated, and as we have already dwelt upon this subject (see p. 13), it will be sufficient for our present purpose simply to advert to the plastic nature of the iron, by which the bars sustained an amount of elongation exceeding that of most other irons.

29. It appears from Table VIII. that the rate of elongation of wrought-iron bars increases with the decrease of their length; thus while a bar of 120 inches has an elongation of ·216 inch per unit of length, a bar of 10 inches has an elongation of ·42 inch per unit of its length, or nearly double what it is in the former case. The relation between the length of a bar and its maximum elongation per unit of length may be approximately expressed by the following formula, viz.:—

$$l = \cdot 18 + \frac{2 \cdot 5}{\mathrm{L}},$$

Digitized by Google

where L represents the length of the bar, and $l$ the elongation per unit of length of the bar.'

30. These results are of some value, as they exhibit the ductility of wrought iron at a low temperature, and also the greatly increased strength which it exhibits with a reduced section under severe strain.

## ON THE STRENGTH OF THE JOINTS OF PLATES WHEN UNITED BY RIVETS AS COMPARED WITH THE STRENGTH OF THE PLATES.

31. To ascertain facts, and to show how nature works in this direction, we are compelled to have recourse to the old but certain test of experiment. This appeared to the author as the only certain method of arriving at truth in physical research. Pursuing, therefore, the old-fashioned expedient, it will be necessary to state, what appears obvious to the most casual observer acquainted with mechanical constructions, that to unite plates together so as to make the joints as secure as if they were continuous and homogeneous in character is a desideratum. It would be desirable, for example, to have the longitudinal sheathing of our ships or plates without joints; but this cannot be done by welding, and, therefore, we have to resort to the expedient of uniting them together by bolts or rivets. Now it has been found that the latter process is by far the strongest and most endurable, as the rivets are generally put in hot and then hammered, or, what is decidedly preferable, compressed by the riveting machine into the holes prepared for their reception. A good rivet requires a head on each side, the same as a bolt and nut; but there is this difference, that the rivet becomes, when carefully inserted, part and parcel of the plate, and when they are duly proportioned as to size and number become equal in strength to the plate itself, minus the parts punched out for the rivets. It is therefore desirable, in every case where plates have to be joined, that they should be united by rivets.

32. In ship building, and in every other construction, such as beams and bridges, where wrought iron forms the whole or the principal part of the material which enters into the construction, it is essential that this part of the inquiry should be explicitly

Digitized by Google

and clearly understood. It is therefore most desirable that the question should be thoroughly investigated, and that all those engaged in constructions of this kind should be fully aware of its importance, not only as regards the acquisition of knowledge, but the heavy responsibility which attaches to works on which the lives and property of the nation and of individuals depend.

Impressed with these views, we venture to submit to the engineer and naval architect the results of experiments, which from time to time and for a long series of years have engaged our attention. In attempting to unite plates by the insertion of rivets we have first to consider—

## I. PUNCHING.

33. This is a very important part of the ship-building process—first, that the holes should be clean and well cut, and that by a perfectly flat steel punch, similar to that shown at A, fig. 6. Secondly, the holes in the plates when put together should be coincident, and should have a common centre, and should cover each other in the manner shown in the annexed sketch, fig. 7. To accomplish this it is desirable that the punching should be done, if possible, by a self-regulating punching machine;* but when this cannot be accomplished the greatest care should be observed on the part of the workman to see that the punching is executed so as to bring the holes coincident with each other, and not to incur the anomalous condition of having them

Fig. 6.

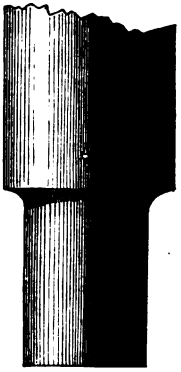
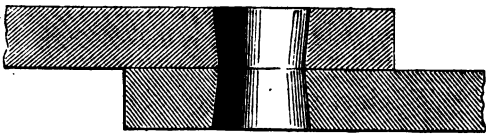


Fig. 7.

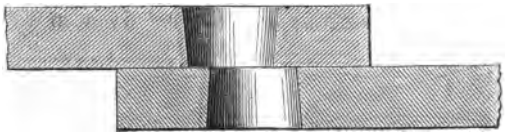


* This has been done by the Jacquard machine of the late Mr. Roberts, with a degree of precision unequalled in self-regulating machines.

Digitized by Google

half-blind, as it is technically called, as shown in fig. 8, or nearly blind altogether—a circumstance which, unfortunately, in rough imperfect work too often occurs.

Fig. 8.



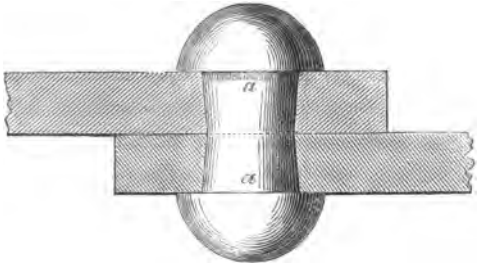
34. It is much to be regretted that more attention is not paid to these operations, as inaccurate punching is seriously detrimental to the plates, and there is nothing which causes more injury to the security and tightness of the joints than bad riveting. The remedy chiefly in use by workmen as a compensation for the want of coincidence in the holes is to drive through both a tapered steel pin or drift, forcing and tearing the plate in every direction; and, in order that they should obey the dictates of physical force (as administered by a sledge-hammer, in the hands of one whose muscular developments are greatly in excess of his reflective functions), the holes are forcibly enlarged and the rivet very imperfectly closed at an oblique angle to the face of the plate. This is a process that cannot be too much condemned, and appears to be the strongest argument against the punch. Some engineers, to avoid this evil, insist on having the holes in the plates drilled, but according to our judgment this system is better adapted to bolts than rivets, as drilled holes are not always perfect, and are never so sound nor yet so secure for rivets as those which come from the punch; and for this reason, that in punching a hole through an iron plate it is not the same as a drilled hole, exactly cylindrical, parallel, or smooth, but the frustrum of a cone, and hence follows the superiority of the joint, as more easily adjusted and more closely incorporated with the plates. It will not be necessary in this place to determine the law by which this particular form is attained; suffice it to observe that the diameter of the punch is to the hole in the die as 1 : 1·15 or 1 : 1·20 for ordinary work, and we have



Digitized by Google

therefore a hole in the plate or the piece punched out, with oblique sides, the angles of which vary in the ratio of the thickness of the plate, and these with coincident holes form a sound and perfect rivet. Now this form of hole is not injurious, but of great value as regards the strength of the joints, as the conical form of the holes is equivalent to a countersunk rivet on each side, as may be seen at *a a*, fig. 9. It is, moreover, highly

Fig. 9.




advantageous in ship building, where the rivets are countersunk on one side, and where a perfectly smooth surface is required for the passage of the currents on all sides of the vessel on the other.

35. To arrive at the strongest form of joint, it is necessary in this case to punch the plates so that the narrow sides of the holes are in contact, as exhibited in fig. 9. This is the more essential, as the heads of the rivets are easier formed, and the holes better filled when performed either by the hammer or by compression. By the latter process—machine riveting—the joints are brought closer in contact by contraction as the rivet cools, and the adhesion of the two surfaces becomes greatly augmented.

## II. RIVETING.

36. During the early stages of iron construction, and as recent as the time to which we have alluded, when iron ship building was first introduced, there was only one system of uniting the joints of iron plates, namely, the overlap single-

Digitized by Google

riveted joint. Now it is widely different, as the variety of purposes to which plates are applied renders a new and entirely different principle of riveting essential. When the double-riveted joint came into use is uncertain, but its advantages were first shown during the progress of the experiments recorded in a paper read before the Royal Society in 1850.* These experiments were conclusive as to the value of the double-riveted joint, but a new system of iron construction has since been developed in the experimental researches which led to the form and construction of the Britannia and the Conway Tubular Bridges. In these structures it was imperative that the joints submitted to tension should be equal, or at least approximate closely, to the strength of the solid plate, and after a great number of experiments it was found that the old system of single and double joint riveting was not only inapplicable, but weak and insecure. This insecurity led to a more extended series of experiments, the results of which we have now to record for the benefit of those who are not acquainted with the facts, and to whom it may be useful in the varied forms of construction as applied to iron ships and bridges.

37. It is stated 'that large vessels composed of iron plates, such as steam boilers, cisterns, ships, &c., cannot be formed on the anvil and the rolling mill. They are composed of many parts, and these parts have to be joined together in such forms as to insure uniformity of strength and effect all the requirements of sound construction.' These observations were written in 1838, and at that time there existed no researches calculated to guide the mechanics and engineers of that day in the construction of vessels whose chief security depended more upon the strength of the joints than the resistance of the plates. In fact, such was our ignorance at the time that most persons believed—engineers amongst them—that the joint was stronger than the plate. Now there could not be a more unfortunate error, as we hope to prove from actual experiment when we come to treat of the different kinds of riveted joints submitted to a tensile strain.

38. To render these views more explicit it will be necessary

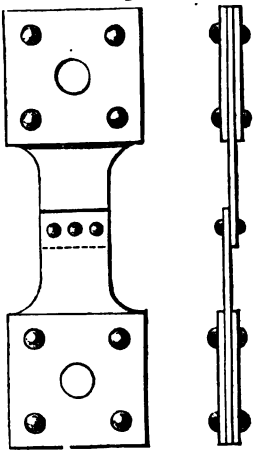
* See 'Philosophical Transactions,' Part II. 1850.



Digitized by Google

to give the results as they occur in the experiments, where the first specimens experimented upon—five in number—indicated the following results :—

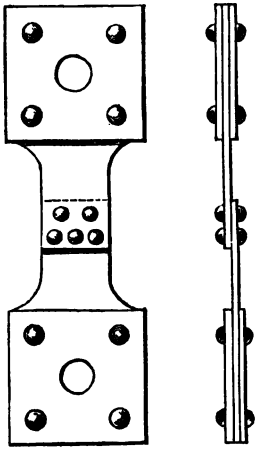
Fig. 10.



| Breaking Weight lbs. | |
|---|---|
| 20,127 | Mean, 18,591 |
| 16,107 | |
| 18,982 | |
| 19,147 | |

In the first experiments the rivets were cut or sheared asunder, showing that the plates were stronger than the rivets. In the four subsequent experiments the rivets were increased in thickness, when the fracture took place through the line of rivet holes, and gave, as above, a mean of 18,591 lbs. on an area of ·44 inches. On referring to the experiments it will be found that an area of ·46 of solid plate broke with 26,168 lbs., and this reduced gives a ratio of 25,030 : 18,591 or as 1 : ·742 as the measure of resistance between the plate and the riveted joint. In other words, there is a loss of 26 per cent. on the joint as compared with the plate.

Fig. 11.



Comparing the double-riveted joint with the solid plate in the same manner as the single-riveted joint, the results obtained were—

| Breaking Weight lbs. | |
|---|---|
| 23,035 | Mean, 23,665 |
| 25,387 | |
| 22,531 | |
| 23,707 | |

or a mean of 23,665 as the breaking weight of the four specimens experimented upon. This, compared with the single joint, gives an excess of strength of 4,047, a ratio of nearly 10 : 8 in favour of the double-riveted joint. This when compared with the solid plate, 25,030 lbs., shows an amount of resistance which

Digitized by Google

approximates closely to the strength of the plate itself; and in one of the experiments it was rather more than equivalent to its ultimate powers of resistance. Reverting, however, to the experiments in detail, and taking the mean breaking weights of the riveted joints, and comparing them with the section of the plate itself, the areas being the same, we have for the tensile strength of plates—

| | Area of Section torn asunder | lbs. |
|---|---|---|
| Solid plate | ·44 | 25,400 |
| Double-riveted joints | ·44 | 23,707 |
| Single-riveted joints | ·44 | 18,590 |

the proportionate strength of the plates and joints. Assuming, therefore, the strength of the plates to be 1,000, we have—

| | |
|---|---|
| For the strength of plates of equal sections | 1000 |
| For the double-riveted joints | 933 |
| For the single-riveted joints | 731 |

From this we may safely assume these ratios as the comparative values of jointed plates of equal sections when acted upon by a force calculated to tear them asunder.

The correct value of the plates, computed from a sectional area taken through the rivet-holes, will therefore be to their riveted joints as 100, 93, and 73, or in round numbers as 10, 9, and 7.

In addition to a loss of nearly one-tenth in the double-riveted joints, and three-tenths in the single ones, it will be observed that the strength of the plates is still further reduced by the quantity of iron punched out for the rivets, and hence the comparison will be with the body of the plate and the strength of the riveted joint respectively.

The results of the last two experiments are identical as to strength. In the first, with the countersunk rivets, the plates were torn asunder; and in the latter the rivets appear the weakest, owing to the increased sectional area of the plates, which in the preceding experiment was reduced by countersinking the rivets.

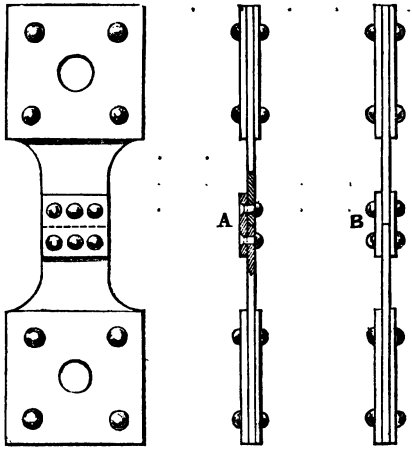
In both experiments it will be observed that the strengths of the rivets are proportional to the strengths of the plates, their powers of resistance being equal, or nearly so. In forty-one ex-

Digitized by Google

periments the sectional area of the rivets was to that of the plates as ·340 to ·347—that is, the sections were nearly equal—and in forty-two additional experiments they were as ·34 to ·44, which accounts for the nature of the fracture in both cases.

39. The next joints experimented upon were what are called flush or butt joints, with covering plates of the form fig. 12; and in these we have for the single-riveted joint, taken from four experiments, one of them having countersunk rivets—

Fig. 12.




| | Breaking Weights lbs. | |
|---|---|---|
| Joint A, with plate on one side | 16,351<br>16,351 | Mean, 16,351 lbs. |
| Joint B, with plates on both sides | 25,723<br>21,355 | Mean, 23,539 lbs. |

Here, it will be observed, is a marked difference between the single-plated joints and those with plates on each side, being in the ratio of 23 : 16. This may be accounted for by the distortion of the single-covering plate, causing the strain to act obliquely upon the plate and the rivets. This was not the case in the double-plated joint, where the plates were not bent, but kept in the line of strain. Two double-riveted plates, jointed with double coverings, one on each side, rather more than half the thickness of the centre plate, were also torn asunder with weights of—

lbs.
27,003
26,059 } giving a mean of 26,731 lbs., or

1,701 lbs. in excess of the weight that fractured the solid plate through the line of the rivet-holes.

40. It will not be necessary to multiply these comparisons, as sufficient data have already been furnished to enable us to calculate the force per square inch, and to resolve the whole into a general summary, exhibiting the relative strengths—1st, of the plates; 2ndly, of the single and double-riveted joints, and

Digitized by Google

lastly, the ratio of the strengths as deduced from the whole series of experiments.

TABLE IX.

GENERAL SUMMARY OF RESULTS AS OBTAINED FROM THE FOREGOING EXPERIMENTS.

| | Cohesive Strength of the Plates. Breaking Weight in lbs. per Square Inch | Strength of double-riveted Joints of equal Section to the Plates, taken through the Line of Rivets. Breaking Weight in lbs. per Square Inch | Strength of single-riveted Joints of equal Section to the Plates, taken through the Line of Rivets. Breaking Weight in lbs. per Square Inch |
|---|---|---|---|
| | 57,724 | 52,352 | 45,743 |
| | 61,579 | 48,821 | 36,606 |
| | 58,322 | 58,286 | 43,141 |
| | 50,983 | 54,594 | 43,515 |
| | 51,130 | 53,879 | 40,249 |
| | 49,281 | 53,879 | 44,715 |
| | 43,805 | ... | 37,161 |
| | 47,062 | | |
| Mean | 52,486 | 53,635 | 41,590 |

The relative strengths will therefore be,—

| | |
|---|---|
| For the plate . . . . . | 1,000 |
| Double-riveted joint . . . . . | 1,021 |
| Single-riveted joint . . . . . | 791 |

From the above it will be seen that the single-riveted joints have lost one-fifth of the actual strength of the plates, whilst the double-riveted have retained their resisting powers unimpaired. These are important and convincing proofs of the superior value of the double joint; and in all cases where strength is required this description of joint should never be omitted.

41. On referring to the experiments contained in the separate tables, there will be found a striking coincidence in the facts tending to establish the principle of double-riveting as superior in every respect to the general practice now in use of the single rivets. It appears when plates are riveted in this manner that the strength of the joints is to the strength of the plates of equal sections of metal as the numbers—

| | Plates | Double Rivet | Single |
|---|---|---|---|
| | 1,000 | : 1,021 and | 791 |
| In a former analysis it was . . | 1,000 | : 933 and | 731 |
| Which gives a mean of . . | 1,000 | : 977 and | 761 |

Digitized by Google

which in practice we may safely assume as the correct value of each. Exclusive of this difference, we must, however, deduct 30 per cent. for the loss of metal punched out for the reception of the rivets; and the absolute strength of the plates will then be to that of the riveted joints, as the numbers 100, 68, and 46. In some cases, where the rivets are wider apart, the loss sustained is, however, not so great; but in boilers and similar vessels, where the rivets require to be close to each other, the edges of the plates are weakened to that extent. In this estimate we must, however, take into consideration the circumstances under which the results were obtained, as only two or three rivets came within the reach of experiment; and, again, looking at the increase of strength which might be gained by having a greater number of rivets in combination, and the adhesion of the two surfaces in contact, which in the compressed rivets by machine is considerable, we may fairly assume the following relative strengths as the value of plates with their riveted joints:—

| | |
|---|---|
| Taking the strength of the plate at . . . . . | 100 |
| The strength of the double-riveted joint would then be . | 70 |
| And the strength of the single-riveted joint . . . | 56 |

These proportions may therefore in practice be safely taken as the standard value of joints, such as used in vessels where they are required to be steam or water-tight, and subjected to pressure varying from 10 to 100 lbs. upon the square inch.

42. Having ascertained the value of single and double-riveted joints in relation to the strength of the plates, we have now to consider another description of riveting, first introduced in the construction of the Britannia and Conway Tubular Bridges. In the history and description of these bridges* it will be found that, in order to attain perfect uniformity in the strength of the joints and plates of the lower parts of the tubes submitted to tension, it was ascertained by direct experiment that the shearing or cutting the rivets when tearing the joint asunder was as nearly as possible as the areas of the rivets and the area of the plates respectively taken through the line of the rivet-holes; that is, if the area of the plate when the holes for the rivets are

* Vide Mr. Fairbairn's work entitled 'An Account of the Construction of the Britannia and Conway Tubular Bridges,' page 68.

Digitized by Google

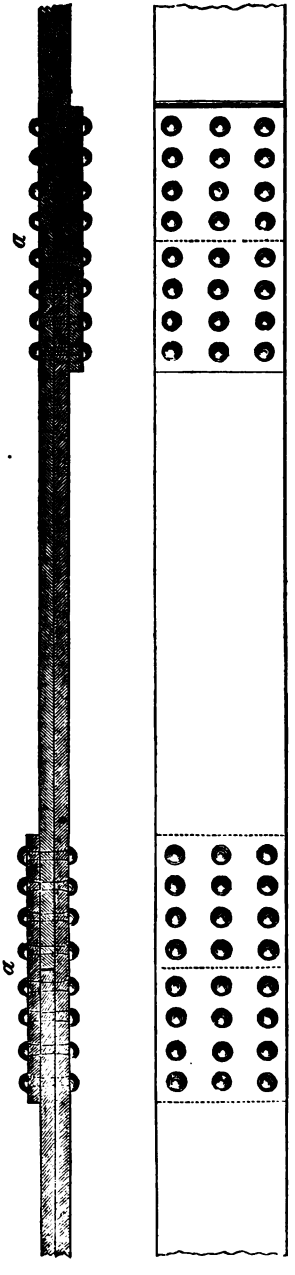
punched out be 100, the area of the rivets should also be 100, and we then have a joint of proportionate strength to that of the plate.

43. There are, however, certain conditions to be observed in every construction where economy in the use of material is considered, namely, that in jointing plates calculated to resist tension, the fewer holes the better, as every perforation tends to weaken the plate in the ratio of the diameter, or the width of the hole punched out. To obviate this, a system of chain-riveting was introduced in 1846, during the experimental investigation which led to the tubular plate and lattice system of construction. In the work referred to to it is stated (page 68) that, 'irrespective of the strength, and other proportions of the tube, I have computed the bottom plates, on the lower side, at one inch thick at the middle.

'I do not, however, look upon them as plates of that thickness, but composed of two plates, each half an inch thick, with tne transverse joints resting upon the solid plate on the one hand, and suspended from it on the other, as the case may be. This will give great uniformity of strength, when treble-riveted, with a covering plate of the same thickness, well attached with tail rivets to prevent curling at the ends, and perforating with as few holes as possible the solid plates, the same as per sketch at *a a*, fig. 13.'

From this it will be seen that the force of tension was carefully investi-

Fig. 13.




Digitized by Google

gated in this inquiry, and in order to prevent injury to the plate, and to form a substantial joint, it was ascertained that a series of smaller rivets in the line of the strain was preferable to having them of larger dimensions across the joint. Having arrived at this conclusion, the principle adopted was according to fig. 13, where twelve rivets on each side of the joint corresponded in area with those in the plates, taken transversely through the line of the rivets, as already described. Had the rivets been five, on the principle of the double joint, instead of twelve on each side (which, by the bye, is probably the best for ship building), they must have been enlarged to double their areas, to balance their powers of resistance to shearing when torn asunder by the force of tension.

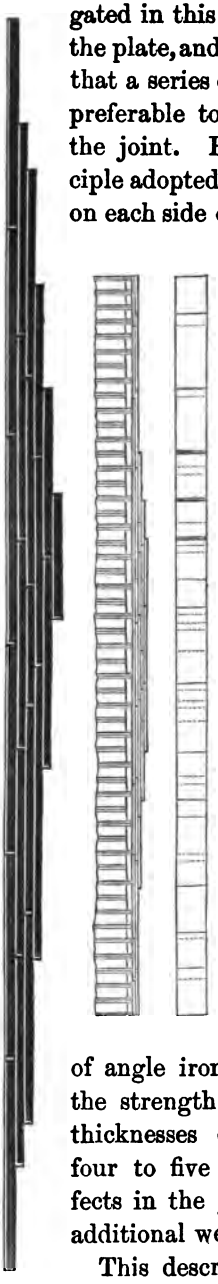


Fig. 14.

44. In the construction of plate girders a system has been adopted to resist tensile fracture, and that is by increasing the thickness of the plates in the middle, where the strains are greatest, to save the use of covering plates. Let us, for example, suppose that fig. 14 represents the bottom plates of a girder of 60 feet span, with plates 10 feet long and 2 feet wide, and we have a continuous line of four rows of rivets throughout the whole length of the girder of 60 feet; and to have all the joints covered, so as to bring every layer of plates into tension, it would require four thicknesses of plates, exclusive of angle irons, which is very objectionable, as regards the strength of the rivets and joints, as two to three thicknesses of plates are much easier riveted than four to five thicknesses. But, exclusive of these defects in the joints, there is an unnecessary loss in the additional weight of the material employed.

This description of joint is, however, not applicable

Digitized by Google

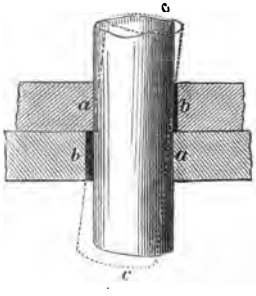
to ship building, as the strakes and stringers never exceed a single thickness of plate, and the only transverse joint suitable in this case is on the chain or double-riveted system. If the latter is adopted, the rivets would require to be made of sufficient strengths, in order to give equal areas with that of the plates through the line of the rivet-holes.

45. Before closing these remarks it may be useful to refer to a paper of Mr. Grantham's, read before the Institution of Naval Architects in 1862, wherein he states 'that the whole question of riveting evidently depends on the form of the rivet-hole; that the usual practice is to punch all the holes in the under side of plates to a templet, observing always that the side from which the rivet is inserted is the lower side when under the press. This causes the slight taper, which punched holes always have, to be in the right direction for the insertion of the rivet. When these plates have been fitted, those for the outer strake are applied, and the exact position of each hole is marked by inserting through the inner plate a round plug, previously dipped in some liquid whiting, or an elaborate and rather complicated templet is made of these holes, by which the outer plate is punched. The plate being, in either process, thus prepared for punching, is taken to the press, and being lifted and guided by a gang of men, each hole is separately punched. Any one who has watched this process with heavy plates knows how impossible it is to form the hole exactly where marked; and I may safely say that, however careful the men may be, the holes, as a rule, are never fair with each other. Their position is represented by two eccentric circles, in as fig. 15, more or less divergent from each other.

Fig. 15.

'The riveter now begins his work, and, with the knowledge that the state of the holes is always such as described, he is prepared with a steel drift, tapered at the point, but nearly parallel in the centre; this is violently driven into the hole by hammers, producing the effect shown in fig. 16, swelling the holes in the plates, as at *a a*, and leaving vacancies at the

Fig. 16.




Digitized by Google

opposite sides, as at *b b*; or, to describe the case more accurately, the drift is forced rather into an oblique position, as shown by the lines *c c*. He then inserts the rivet, which is hammered up in the usual way. If the rivet be very hot, and the hole not very irregular, by dint of hard blows the hole is well filled, and the work sound, though about this there is no certainty. But suppose the hole is very much distorted, the countersink half destroyed, and an abrupt angle at the centre caused by one plate partly overlapping the hole of the other, the effect is then such as is described in fig. 17: the holes are not filled, and the rivet when severely tested becomes loose. There are, of course, all degrees of distortion; some so great that the head of the rivet will scarcely conceal the vacancy. I have frequently seen cases similar to that shown in fig. 18. It is evident that wherever this vacancy occurs, however small it may be, the efficiency of the rivet is greatly reduced; and, supposing further (a case which occurs every day in our very best ships) that in the same seam both the rivets and joints have the defects above described, how greatly must the general strength of the ship be diminished! To meet these defects large additions to the quantity of the iron have been made.'

Fig. 17.

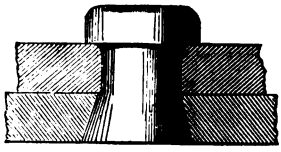


Fig. 18.

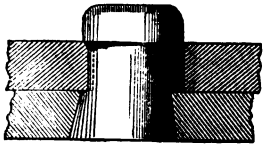
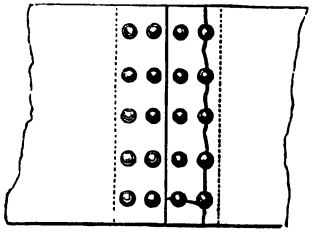


Fig. 19.



46. Messrs. Martin and Ritchie, surveyors of Lloyd's, have also directed their attention to the riveting of iron ships, and a series of experiments, under the immediate superintendence of Mr. W. F. Mumford, proves that out of thirty differently united joints, those

* On this question of imperfect punching it seldom occurs that the hammered rivets are tight or made to fill the hole. Machine riveting or those inserted by compression almost invariably fill the hole, as the head of the rivet is not formed until the vacancy in the hole is effectually filled.

Digitized by Google

upon the chain principle with the rivets in the line of the strain, as shown in fig. 19, are the strongest and best application, and approximate closer to the strength of the solid plate, taken through the line of the rivet-holes, than any of the others experimented upon. This has already been proved by previous experiments on the tensile strength of the joints of horizontal girders and iron bridges.

### III. RIVETS.

47. On this subject we have to consider the diameter, pitch, and length necessary to be observed in forming sound steam and water-tight joints, without injury to the plates beyond the amount of metal punched out for the reception of the rivets, and in this we are assisted by the investigation to which we have referred, and the remainder we embody in the text for the sake of convenience, as under:—

In the pursuit of the foregoing inquiry I was naturally led to the consideration of the best proportions and best forms of riveting plates together. I investigated this subject with great care; and, from my own personal knowledge and that of others, have collected a number of practical facts, such as long experience alone could furnish. From these data I have been enabled to complete the following table, which for practical use will be found highly valuable in proportioning the distances and strength of rivets in joints requiring to be steam or water-tight.

TABLE X.

TABLE EXHIBITING THE STRONGEST FORMS AND BEST PROPORTIONS OF RIVETED JOINTS, AS DEDUCED FROM THE EXPERIMENTS AND ACTUAL PRACTICE.

| Thickness of Plates in Inches | Diameter of Rivets in Inches | | Length of Rivets in Inches | | Distance of Rivets from Centre to Centre in Inches | | Quantity of Lap in single Joints in Inches | | Quantity of Lap in double-riveted Joints in Inches |
|---|---|---|---|---|---|---|---|---|---|
| ·19 = 3/16 | ·38 | 2 | ·38 | 4·5 | 1·25 | 6 | 1·25 | 6 | For the double-riveted joint add two-thirds of the depth of the single lap. |
| ·25 = 4/16 | ·50 | | 1·13 | | 1·50 | | 1·50 | | |
| ·31 = 5/16 | ·63 | | 1·38 | | 1·63 | 5 | 1·88 | | |
| ·38 = 6/16 | ·75 | | 1·63 | | 1·75 | | 2·00 | 5·5 | |
| ·50 = 8/16 | ·81 | 1·5 | 2·25 | | 2·00 | 4 | 2 25 | 4·5 | |
| ·63 = 10/16 | ·94 | | 2·75 | | 2·50 | | 2·75 | | |
| ·75 = 12/16 | 1·13 | | 3·25 | | 3·00 | | 3·25 | | |

Digitized by Google

The figures 2, 1·5, 4·5, 6, 5, &c., in the preceding table are multipliers for the diameter, length, and distance of rivets, also for the quantity of lap allowed for the single and double joints. These multipliers may be considered as proportionals of the thicknesses of the plates to the diameter, length, distance of rivets, &c. For example, suppose we take $\frac{3}{8}$ plates, and require the proportionate parts of the strongest form of joint, it will be—

| | | |
|---|---|---|
| ·375 × 2 | = ·750 | diameter of rivet, $\frac{3}{4}$ inch. |
| ·375 × $4\frac{1}{2}$ | = 1·688 | length of rivet, $1\frac{3}{4}$ inch. |
| ·375 × 5 | = 1·875 | distance between rivets, $1\frac{7}{8}$ inch. |
| ·375 × $5\frac{1}{2}$ | = 2·063 | quantity of lap, 2 inches. |
| ·375 × $5\frac{1}{2}$ + $\frac{3}{8}$ | = 3·438 | quantity of lap for double-riveted joint, $3\frac{1}{2}$ inches. |

·75, 1·68, 1·87, 2·06, and 3·43 are therefore the proportionate quantities necessary to form the strongest steam or water-tight joints on plates three-eighths of an inch thick.

Digitized by Google

# CHAPTER IV.

## ON THE PROPERTIES OF IRON—(*continued*).

### THE RESISTANCE OF PLATES AS APPLIED IN DIFFERENT FORMS TO THE FORCE OF COMPRESSION.

1. We have already noticed, when treating of the tensile strain to which a ship is subjected, that another equally important force is in operation in the movements of the vessel—that of crushing or compression. This is more apparent in iron than in wooden structures, as thin plates are liable to distortion when forcibly compressed in the direction of their lengths, and in ship building, as in tubular girder bridges, this tendency to '*pucker*' requires to be carefully guarded against. In conducting the experiments for the Conway and Britannia Bridges this weakness was carefully considered, and as the strains in that of a ship and a monstrous tubular girder are analogous, it is requisite in both structures that the forces should be clearly understood, and the tendency to buckle prevented.

To enable the practical ship builder to acquire this knowledge, and become acquainted with the laws which govern iron structures of different forms and conditions, it will be necessary to investigate this question attentively, and endeavour to establish sound principles of construction in the minds of those who are entrusted with designs of such importance.

2. To construct a perfectly secure iron ship, every one of the transverse joints should be planed, in order that the ends of the plates may butt and form a solid joint. This connection is the more important, as the action of a vessel pitching at sea (as before explained) is a continued series of alternate strains of tension and compression at midships. By extending the weights or cargo in the direction of the bows and stern these strains

Digitized by Google

are increased, and this, as a general rule, should be avoided by concentrating the cargo as much as possible at the centre of the ship.

### FLEXURE, CRUSHING, AND COMPRESSION.

3. The immediate effect of the transverse strains to which vessels of great length are exposed is alternately to tear and compress those portions of the vessel above and below the neutral axis. It is therefore important that the resistances of these opposing forces should be clearly defined, and in order to simplify the investigation it will be necessary to consider the measure of the forces required to crush a cubic inch of different kinds of material. The table following is compiled from the results of recent experiments.

TABLE XI.—ON COMPRESSION.

| No. of Expt. | Specific Gravity | Description of Material | Pressure per Square Inch | | Ultimate Compression in Inches per Unit of Length | Remarks |
|---|---|---|---|---|---|---|
| | | | lbs. | tons | | |
| 1 | ... | Steel very hard, both ends flat | 269,419 | 120·27 | ·0260 | Not crushed |
| 2 | ... | Steel softer, one end round | 202,543 | 90·46 | ·1162 | Crushed |
| 3 | ... | Cast iron, both ends flat | 123,951 | 55·32 | ·0665 | ,, |
| 4 | ... | Cast iron, one end round | 60,180 | 26·86 | ·1305 | ,, |
| 5 | ... | Wrought iron, both ends flat | 165,763 | 73·99 | ·2815 | Flattened |
| 6 | ... | Wrought iron, one end round | 111,761 | 49·89 | ·2165 | ,, |
| 7 | ·980 | Box ... ... | 9,771 | 4·36 | ... | Crushed |
| 8 | ·700 | Dry English oak | 9,509 | 4·24 | ... | ,, |
| 9 | ·780 | Ash ... ... | 8,683 | 3·87 | ... | ,, |
| 10 | ·753 | Spanish mahogany ... ... | 8,198 | 3·65 | ... | ,, |
| 11 | ·660 | Sycamore ... | 7,082 | 3·16 | ... | ,, |
| 12 | ·640 | Birch ... ... | 6,402 | 2·85 | ... | ,, |
| 13 | ·580 | Red deal ... | 5,748 | 2·56 | ... | ,, |
| 14 | ·540 | Cedar ... ... | 5,674 | 2·53 | ... | ,, |
| 15 | ·560 | Yellow pine ... | 5,375 | 2·39 | ... | ,, |

4. In the experiments by the late Professor Hodgkinson on cast iron, it is interesting to observe that the resistance of cast-

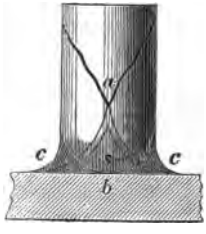
Digitized by Google

iron columns with perfectly flat ends yielded to a force of about 55 tons, whilst the specimens of the same metal with one end rounded gave way with only 26½ tons, rather less than one-half the load required to crush the flat-ended ones.

It is a curious but interesting fact (provided the same law governs the force of impact as that of dead pressure) that the round end should cause the column to lose one-half of its powers of resistance as compared with both ends flat. This may be accounted for by the following law of fracture:—

5. Taking, for example, the cylinder *a*, with a rounded end forcibly pressed against a steel plate *b*, it is crushed by (a fixed law observable in every description of crystalline substance) the part *s* forming itself into a cone, which, acting as a wedge, splits off the parts *c c* at the angle of least resistance, and these, sliding over its sides, are broken in pieces on the surface of the plate.

Fig. 20.




At Shoeburyness the same results and law of fracture were observable in all the experiments with spherical and round-ended shot. In every instance where the shot was broken in pieces the fractured parts took the same direction, forming a cone or central core similar to that shown at *s*, as exhibited in the experiments with the round-ended cylinders.

6. The law of fracture has been carefully investigated by the late Professor Hodgkinson, in his paper on 'Pillars.' It is there clearly shown that the resistances of columns, when broken by compression, were as follows, viz.:—

| | |
|---|---|
| Taking a column with rounded ends at . . . | 100 |
| A column with one end round and one flat gave . . | 200 |
| And a column with both ends flat . . . . | 300 |

Or the middle is an arithmetical mean between the other two, the resistances being in the ratio of 1, 2, 3. These important facts, it would appear, bear directly upon the form necessary to be observed in the manufacture of projectiles; as we find the projectile, if made round at the ends, loses nearly one-half of



Digitized by Google

its resistance to pressure, and assuming that the same law applies to a force of impact or to a blow which tends to rupture or break a plate in pieces, it then follows that the round end is not the best form for elongated shot.

7. My own experiments, given in Table XI., do not exactly agree with Professor Hodgkinson's, the ratio of resistance of a column with one end rounded to that of a column with both ends flat being as 1·5 : 2, instead of 1 : 2, as in his experiments; a discrepancy probably explained by considering that he employed cast-iron pillars of from 30 to 40 diameters in length, whereas my own were only two diameters long. Professor Hodgkinson has indeed expressed an opinion that the difference of the strengths of the three forms of pillars becomes less according as the number of times which the length of the pillar exceeds the diameter decreases, which in some measure confirms the results obtained above. But on this I may observe that the conclusion being founded on a very limited number of experiments on wrought-iron columns of 15 to 30 diameters long, compared with others 60 diameters long, has been, in my opinion, too hastily assumed as a general law; with wrought iron, especially, the crushing up of the rounded ends would soon bring pillars of that form into the condition of flat-ended pillars, when their breaking weights approached the crushing strength of the material; a conclusion confirmed by observing that the cases in question are exactly those in Mr. Hodgkinson's table in which the breaking weights of the pillars were greatest. However this may be, the experiments I have given show, that short cylinders with flat ends have not twice the strength of similar pillars with one end rounded. From this it would appear, that the law for short cylinders is not the same, but altogether different from that obtained by Professor Hodgkinson for long pillars.

8. These discrepancies between my own experiments and those of Professor Hodgkinson led to further inquiries into the law which seems to govern short bolts or columns of two diameters in length. To account for these discrepancies the experiments were extended to columns with both ends rounded, and what renders these experiments interesting is

Digitized by Google

that in short columns with both ends rounded the power of resistance is nearly the same as in those with one end flat and one end rounded; and, moreover, they appear to follow a different law from that of Professor Hodgkinson's long columns, which, in most cases, broke by flexure. The difference in strength between short columns with both ends rounded and those with one end flat and one end rounded is almost inappreciable, as will be seen by comparing the values as follows:—

| | Tons per Square Inch |
|---|---|
| Columns of two diameters long, with flat ends, crushed with . . . | 55·32 |
| Columns of two diameters long, with one end rounded and one flat. | 26·86 |
| Columns of two diameters long, with both ends rounded . . . . | 23·88 |

So that the difference between these may be taken as the numbers 55, 27, and 24; or, in other words, in the ratio of 1 : ·49 with one end rounded and one end flat (the flat ends representing unity), and as 1 : ·44 with both ends rounded, which is comparatively a slight difference between those with both ends rounded and those with one end flat and one end rounded.

9. It has been ascertained that the effect of compression on any substance is to shorten its height, and to enlarge its surface by increasing its bulk horizontally. Supposing, however, that the substance is confined and prevented from spreading in that direction, it will then be found that the weight of one ton compresses wrought iron about $\frac{1}{10000}$ part of an inch, and in cast iron, which is much harder, we meet with this anomalous condition, namely, that a similar specimen is shortened or compressed $\frac{2}{10000}$ parts of an inch, being double that of wrought iron, with the same weight. This arises, probably, from the porosity of its crystalline structure as compared with wrought iron, which undergoes a process of consolidation by hammering and rolling.

10. Another curious circumstance connected with wrought iron, when submitted to compression, is that it will bear almost any amount of pressure, provided it be sufficiently ductile. It, however, suffers permanent distortion by a comparatively light weight, and its resisting powers are seriously injured with



Digitized by Google

12 tons per square inch. Beyond this it may be compressed to any extent, provided it be sufficiently plastic, by enlarging its base and shortening its height till it becomes a perfectly flat plate. With 12 tons its elasticity is much impaired, and it takes a considerable permanent set, which increases as the squares of the load, and in most cases, where these effects are important, it is desirable, if not absolutely necessary, to keep within the limits of its elasticity.

11. We have seen that both the top and the bottom of a ship have to resist a force of compression analogous to that sustained by columns, and that being the case, it is desirable that we should become acquainted with the resistances of wrought iron of different forms in that direction. It is also necessary to ascertain the laws by which these resistances are regulated in the relative positions of the upper deck and the lower hull of a ship. Effectively to resist these forces, it is obvious that the covering plates below and the stringer plates above require to be stiffened; or, in other words, to be converted into a series of horizontal pillars calculated to offer an equally powerful resistance to compression as they do to tension. It was for that object that the late Professor Hodgkinson undertook—in conjunction with the author, when engaged in the construction of the Britannia and Conway Bridges—a laborious series of experiments on the compression of wrought-iron plates and tubes, which form the top of these immense structures. These experiments are not less applicable to the construction of iron ships than to that of tubular bridges, and we may therefore find it serviceable to offer a few remarks upon them.

12. In the earlier experiments it was found that round, square, and rectangular tubes of a given length presented nearly double the resisting powers when the same weight of material was applied in the form of a tube or cell than it did in the form of a solid plate. These facts were subsequently confirmed by Professor Hodgkinson's experiments, of which the following tables are abstracts:—

Digitized by Google

TABLE XII.—RESISTANCE OF PLATES OF WROUGHT IRON TO A CRUSHING FORCE, THE ENDS OF THE PLATES BEING TURNED FLAT, AND PERFECTLY BEDDED AGAINST THE PARALLEL PLANES, BETWEEN WHICH THEY WERE COMPRESSED. THE RESULTS GIVEN ARE THE MEANS OF THE EXPERIMENTS MADE.

| No. of Experiment | Length of the Plate or Bar | Weight of the Plate | Lateral Dimensions of the Plate | Breaking Weight, or Weight of greatest Resistance | Weight of greatest Resistance per Square Inch of Section |
|---|---|---|---|---|---|
| | ft. in. | lb. oz. | inches | lbs. | lbs. tons |
| 1 | 10 0 | ... | 2·98 × ·497 = 1·481 | 1,099 or 1,222 from first experiment | $\frac{1222}{1·499}$ = 815 = ·364 |
| 2 | 10 0 | 76 $7\frac{3}{4}$ | 3·01 × ·766 = 2·306 | 7,793 | $\frac{7793}{2·306}$ = 3,379 = 1·508 |
| 3 | 10 0 | 100 0 | 2·99 × ·995 = 2·975 | 12,735 | $\frac{12735}{2·975}$ = 4,281 = 1·911 |
| 4 | 10 0 | 151 15 | 3·00 × 1·51 = 4·53 | 46,050 | $\frac{46050}{4·53}$ = 10,165 = 4·538 |
| 5 | 7 6 | 25 $10\frac{3}{4}$ | 1·024 × 1·025 = 1·0496 | 10,236 | $\frac{10236}{1·0496}$ = 9,752 = 4·354 |
| 6 | 7 6 | 37 $14\frac{3}{4}$ | 2·983 × ·5023 = 1·4983 | 3,614 | $\frac{3614}{1·4983}$ = 2,412 = 1·076 |
| 7 | 7 6 | 69 14 | 3·005 × ·9955 = 2·9915 | 29,619 | $\frac{29619}{2·9915}$ = 9,901 = 4·425 |
| 8 | 7 6 | 116 3 | 3·00 × 1·53 = 4·59 | 91,746 | $\frac{91746}{4·59}$ = 19,988 = 8·923 |
| 9 | 7 6 | 148 3 | 5·86 × ·995 = 5·8307 | 54,114 | $\frac{54114}{5·8307}$ = 9,281 = 4·143 |
| 10 | 5 0 | 16 $13\frac{3}{4}$ | 1·024 × 1·024 = 1·0486 | 18,106 | $\frac{18106}{1·0486}$ = 17,267 = 7·709 |
| 11 | 5 0 | 25 2 | 2·98 × ·507 = 1·511 | 8,469 | $\frac{8469}{1·511}$ = 5,605 = 2·502 |
| 12 | 5 0 | 38 $3\frac{1}{4}$ | 3·01 × ·767 = 2·309 | 29,955 | $\frac{29955}{2·309}$ = 12,973 = 5·79 |
| 13 | 5 0 | 49 $8\frac{3}{4}$ | 3·01 × ·995 = 2·995 | 54,114 | $\frac{54114}{2·995}$ = 18,068 = 8·066 |
| 14 | 5 0 | 101 $0\frac{1}{2}$ | 5·84 × 996 = 5·8166 | 102,946 | $\frac{102946}{5·8166}$ = 17,699 = 7·901 |
| 15 | 2 6 | 8 $7\frac{1}{2}$ | 1·0235 × 1·0235 = 1·0475 | 26,530 | $\frac{26530}{1·0475}$ = 25,327 = 11·307 |
| 16 | 2 6 | 12 $11\frac{1}{3}$ | 2·9867 × ·5026 = 1·5011 | 25,299 | $\frac{25299}{1·5011}$ = 16,853 = 7·524 |
| 17 | 2 6 | 19 3 | 3·01 × ·763 = 2·297 | 63,786 | $\frac{63786}{2·297}$ = 27,769 = 12·396 |
| 18 | 2 6 | 24 $8\frac{1}{4}$ | 3·00 × ·996 = 2·988 | 88,610 | $\frac{88610}{2·988}$ = 29,655 = 13·239 |
| 19 | 1 3 | 4 3 | 1·023 × 1·023 = 1·0465 | 36,162 | $\frac{36162}{1·0465}$ = 34,555 = 15·426 |
| 20 | 0 $7\frac{1}{2}$ | 2 $1\frac{3}{4}$ | 1·023 × 1·023 = 1·0465 | 50,946 | $\frac{50946}{1·0465}$ = 48,683 = 21·733 |
| 21 | 0 $3\frac{3}{4}$ | 1 $0\frac{1}{2}$ | 1·023 × 1·023 = 1·0465 | ... | Weight of greatest resistance not obtained. $\frac{55202}{1·0465}$ = 52,749 = 23·549 = Weight sustained without fracture, or much flexure, though the length was considerably reduced. |

Digitized by Google

13. On comparing the plates of the same width and thickness it will be found that a plate or bar 3 inches wide by ½ inch thick, and 2 feet 6 inches long, will sustain three times the weight that a similar plate 5 feet long will sustain; in fact, it is three times stiffer, or in the ratio of 25299 : 8469, or nearly as 3 : 1; and this corresponds with the sections of greatest resistance, which are also in the ratio of 3 : 1. Again, bars of the same length, but of different thicknesses, appear to follow a different law; as we find in the 11th and 13th experiments, recorded in the table, that it requires a weight of 54,114 lbs. to produce flexure on the 5 feet long inch-thick plate, whereas 8,469 lbs. crippled the ½-inch plate; showing that the inch-thick plate was more than six times stiffer than the ½-inch, or, in other words, their relative powers of resistance were in the ratio of 6·4 : 1. On comparing the weights of greatest resistance per square inch of section, widely different results are obtained, as may be seen from the above experiments on the 5-inch long plates 1 inch and ½ inch thick, where the proportions are respectively 8·066 and 2·502, or as 3·2 : 1, which indicates that the ultimate powers of resistance to flexure varies as the cube of the thickness.

The two following tables exhibit the resistance of circular and rectangular tubes to the force of compression:—

TABLE XIII.—RESISTANCE OF CIRCULAR TUBES, ALL 10 FEET LONG, TO A FORCE OF COMPRESSION IN THE DIRECTION OF THEIR LENGTH.

| No. of Tube | External Diameter of the Tube | Internal Diameter of the Tube | Thickness of the Plates of the Tube | Weight of greatest Resistance | Area of Section of Tube | Weight of greatest Resistance per Square Inch |
|---|---|---|---|---|---|---|
| | inches | inches | inches | lbs. | inches | tons |
| 1 | 1·495 | 1·292 | ... | 6,514 | ·4443 | 6·55 |
| 2 | 1·964 | 1·755 | ... | 14,158 | ·6104 | 10·35 |
| 3 | 2·49 | 2·275 | ... | 23,958 | ·8045 | 13·29 |
| 4 | 2·35 | 1·865 | ... | 34,516 | 1·605 | 9·60 |
| 5 | 2·34 | 1·91 | ·215 | 31,828 | 1·4353 | 9·901 |
| 6 | 2·995 | 2·693 | ... | 37,356 | 1·349 | 12·362 |
| 7 | 4·05 | 3·772 | ... | 47,212 | 1·7078 | 12·34 |
| 8 | 4·06 | 3·75 | ·150 nearly | 49,900 | 1·9015 | 11·71 |
| 9 | 6·366 | 6·106 | ·1298 | 91,402 | 2·547 | 16·021 |
| 10 | 6·187 | ... | ·0939 | 60,075 | 1·799 | 14·908 |

These results are interesting, as they exhibit the comparative merits of each tube in relation to its diameter, thickness, &c.

Digitized by Google

TABLE XIV.—RESISTANCE OF RECTANGULAR TUBES, ALL 10 FEET LONG, TO A FORCE OF COMPRESSION IN THE DIRECTION OF THEIR LENGTH.

| External Dimensions of Tube | Thickness of Plates of Tube | Weight with which buckling or perceptible Undulation was observed | Weight of greatest Resistance | Form of Section of Tube | Area of Section of Tube | Weight per Square Inch of greatest Resistance |
|---|---|---|---|---|---|---|
| inches | inch | lbs. | lbs. | | inches | tons |
| 4·1 × 4·1 | ·03 | ... | 5,534 | | ·504 | 4·902 |
| 4·1 × 4·1 | ·06 | ... | 19,646 | | 1·0200 | 8·5986 |
| 4·25 × 4·25 | ·083 | 29,290 | 37,354 | | 1·484 | 11·237 |
| 4·25 × 4·25 | ·134 | 46,314 | 51,690 | | 2·3947 | 9·636 |
| 8·175 × 4·1 | ·061 | 13,209 | 23,289 | | 1·532 | 6·786 |
| 8·5 × 4·75 | ·264 | ... | 197,163 | | 7·326 | 12·015 |
| 8·4 × 4·25 | ·26 and ·126 | 99,916? | 206,571 = 92·2 tons | | 6·89 nearly | 13·3845 |
| 8·1 × 4·1 | ·059 | 37,401 | 43,673 | | 1·885 | 9·877 (Not crushed with 11·12 tons.) |
| 8½ × 4¾ | ¼ nearly | ... | ... | | 8·3466 | |
| 8·1 × 8·1 | ·06 nearly | 15,897 | 27,545 | | 2·070 | 5·926 |
| 8·37 × 8·37 | ·139 | 82,475 | 100,395 | | 4·9262 | 9·098 |
| 8·5 × 8·375 | ·2191 | ... | 198,955 | | 7·7367 | 11·48 |
| 8·5 × 8·4 | ·245 and ·238 | ... | ... | | 8·4665 | (Not crushed with 11·015 tons.) |
| 8·1 × 8·1 | ·0637 | 56,630 | 70,070 | | 3·551 | 8·809 |
| 8·1 × 8·1 | ·0637 | 46,635 | 82,027 | | 3·551 | 10·312 |

14. Mr. Edwin Clark, in his work on the Tubular Bridges, analysed the above tables of resistances to flexure with great care, and, finding that the investigation is of equal importance in its application to iron ships as it is to tubular bridges, we deem it necessary, for the information of the naval architect, to insert the following abstract. Mr. Clark states 'that the method by which the laws we have already announced were derived by Mr. Hodgkinson from these experiments was as follows, and will serve as an example of practical analytical reasoning:—

'First, to determine the powers of the length to which the breaking weight was proportional, the other dimensions being supposed to remain constant.

'Selecting from the foregoing table those experiments in

Digitized by Google

which the section was the same, and the plates or bars only differ in length, and taking, first, a mean from those experiments where the plates were each 3 inches broad and 5 inches thick, we find that when these plates were $7\frac{1}{2}$ feet long they were bent beyond further resistance by a weight of 3,501 lbs., and when they were $2\frac{1}{2}$ feet long by 27,372 lbs.

'Now, supposing the resistance to be inversely proportional to $l^n$, that is, to some constant power ($n$) of the length, we have to determine the value of $n$. We shall evidently have:

$$(2\tfrac{1}{2})^n : (7\tfrac{1}{2})^n :: 3501 : 27372$$
$$\text{or } 1^n : 3^n :: 3501 : 27372$$
$$\therefore 3^n = \frac{27372}{3501} = 7{\cdot}81834$$
$$\text{and } n \log. 3 = \log. 7{\cdot}81834$$
$$n = \frac{{\cdot}8931144}{{\cdot}4771212} = 1{\cdot}87$$

'Taking from the table another set, where each plate was of the same lateral dimensions as before, when the plates were $2\frac{1}{2}$ feet long, we have, as above, the breaking weight = 27,372 lbs.; and when the bars were 5 feet long it was 8,469. Hence, as before,

$$(2\tfrac{1}{2})^n : 5^n :: 8469 : 27372$$
$$\text{or } \left(\frac{5}{2\frac{1}{2}}\right)^n = \frac{27372}{8469} = 3{\cdot}23202$$
$$\therefore n \log. 2 = \log. 3{\cdot}23202$$
$$\text{and } n = 1{\cdot}69$$

'Again, selecting from the table bars each 3 inches broad and 1 inch thick, when 5 feet long the breaking weight was 55,010 lbs., and when 10 feet long, 11,932 lbs.; hence

$$1^n : 2^n :: 11932 : 55010$$
$$\text{or } 2^n = 4{\cdot}60945$$
$$\therefore \log. 2^n = \log. 4{\cdot}60945$$
$$\text{whence } n = 2{\cdot}20$$

'Again, with bars each 3 inches broad and $1\frac{1}{2}$ inch thick, when 10 feet long the breaking weight is 46,050 lbs.; when $7\frac{1}{2}$ feet long, 91,746 lbs.

Digitized by Google

$$\therefore (7\tfrac{1}{2})^n : (10)^n :: 46050 : 91746$$

$$\left(\frac{10}{7\frac{1}{2}}\right)^n \text{ or } (1\tfrac{1}{3})^n = 1{\cdot}99231$$

$$n \text{ log. } 1\tfrac{1}{3} = \text{log. } 1{\cdot}99231$$

$$\text{whence } n = 2{\cdot}39$$

'Lastly, selecting bars each 3 inches wide and 1 inch thick, when 10 feet long the breaking weight is 11,932 lbs., and when $2\frac{1}{2}$ feet long, 83,682 lbs.

$$\therefore (2\tfrac{1}{2})^n : (10)^n$$

$$\text{or } 1^n : 4^n :: 11932 : 83682$$

$$4^n = 7{\cdot}01324$$

$$\text{whence } n = 1{\cdot}40$$

'Now, adding together these five values of $n$ and taking the mean, we get

$$n = \frac{1{\cdot}87 + 1{\cdot}49 + 2{\cdot}20 + 2{\cdot}39 + 1{\cdot}4}{5} = 1{\cdot}91;$$

or the power of the length to which the breaking weight is inversely proportional is the 1·9 power, or the square very nearly, as we before assumed.

'To determine, secondly, the power of the thickness to which the breaking weights obtained by experiment were proportional.

'Selecting from the table some bars of the same length, but differing in thickness, we find that two bars, each $7\frac{1}{2}$ feet long, but which were respectively 3 inches broad and $\frac{1}{2}$ inch thick, and 3 inches broad and $1\frac{1}{2}$ inches thick, broke, the first with 3,501 lbs., the second with 91,746 lbs.

'Now, supposing the resistance to the proportional to be $d^n$, that is, to some constant power $n$, of the thickness $d$, we have to determine the value of $n$. We have, therefore,

$$(\tfrac{1}{2})^n : (1\tfrac{1}{2})^n$$

$$\text{or } 1^n : 3^n :: 3501 : 91746$$

$$\therefore 3^n = \frac{91746}{3501} = 26{\cdot}20565$$

$$\text{whence } n \text{ log. } 3 = \text{log. } 26{\cdot}20565$$

$$n = \frac{\text{log. } 26{\cdot}20565}{\text{log. } 3}$$

$$= \frac{1{\cdot}4183950}{{\cdot}4771213} = 2{\cdot}97.$$

Digitized by Google

'Again, selecting two bars, each 7 feet long, the one whose section was $2{\cdot}97 \times 1{\cdot}05$ inches bore 11,932 lbs.; the other, whose section was $3{\cdot}0 \times 1{\cdot}51$ inches, bore 46,050 lbs.: the depth varies as 1 : 1·51 nearly.

$$\therefore\ 1^n : (1{\cdot}51)^n :: 11932 : 46050$$
$$(1{\cdot}51)^n = 3{\cdot}85937$$
$$n = \frac{\text{log. } 3{\cdot}85937}{\text{log. } 1{\cdot}51} = 3{\cdot}27$$

'Lastly, selecting two bars, each 5 feet long, the one whose section was $2{\cdot}98 \times {\cdot}509$ inches bore 8,469 lbs.; the other, whose section was $3{\cdot}0 \times 1{\cdot}0$ inches, bore 55,010 lbs. the depths being when reduced as to breadth, as 1 to 1·97, we have

$$1^n : (1{\cdot}97)^n :: 8669 : 55010$$
$$\text{or } (1{\cdot}97)^n = 6{\cdot}4954$$
$$\text{or } n = \frac{\text{log. } 6{\cdot}4954}{\text{log. } 1{\cdot}97} = 2{\cdot}76$$

'Again, adding together these three values of $n$ to obtain the mean, we have

$$n = \frac{2{\cdot}97 + 3{\cdot}27 + 2{\cdot}76}{3} = 3 \text{ exactly,}$$

that is, the resistance varies exactly as the cube of the thickness, as we have before assumed.

'But square pillars have their strengths as the fourth powers of their diameters, or as the cube of their thickness, into their width, regarding them as narrow plates; hence all long pillars, or plates used as pillars, have their breaking weights nearly proportional to their width and to the cube of their thickness directly, and to the square of their length inversely, both theoretically and experimentally. And also all similar pillars, or plates used as pillars, have their strength proportional to the square of their like lineal dimensions.

'The last very important deduction at once follows from what we have demonstrated, for if we suppose a plate in every respect similar to another, and of $n$ times the dimensions, *but only of such dimensions,* that each fails by flexure when used as a pillar, the strength of the second plate will be $n^3$ times as great on account of its increase of thickness, $n$ times as great on

Digitized by Google

account of its increase in width, and $\frac{1}{n^2}$ times as great on account of its increase of length. It will thus be altogether $\frac{n^3 n}{n^2}$ or $\frac{n^4}{n^2}$ or $n^2$ times as strong.'

15. 'We thus see how erroneous a conclusion would be drawn from *thin* models, as to the buckling of the top, in larger and similar structures, as was the case with the preliminary experiments on thin circular and elliptical tubes, which were condemned on this account; for the top of these tubes was merely a pillar failing from flexure, and had similar tubes been constructed of larger dimensions, then the strength of the top to resist buckling or flexure would have been as the square of the lineal dimensions of increase, until the pillars or thickness became of sufficient dimensions to resist buckling altogether, and to fail by crushing. The curvature in the top of these tubes was, in fact, favourable to the resistance of flexure; a flat plate would have buckled with less strain.

16. 'The limit of 16 tons per inch cannot, however, be exceeded practically, whatever the form. This limit, it will be observed, is nearly approached in the inch square bars in experiment No. 16, which were 15 inches long; in the next experiment the bar was practically crushed with about 16 tons, although it carried considerably more; and we shall hereafter see that with the large models, with cells, the top was destroyed by compression with about 14·8 tons per square inch.

17. 'However valuable, in numberless practical cases, these interesting experimental confirmations of the theory of pillars may prove, they are evidently not directly applicable to the structure which led to them. The top of the Britannia Bridge, though closely analogous, is not a simple pillar or plate subjected to compression. When failure takes place in the top of an ordinary tube by *actual compression*, it will be found to have sustained little more than 16 tons per square inch of its transverse section, and no alteration of its manner of construction would be of any avail. But should it fail by buckling or flexure, its breaking strain would fall short of this quantity, and any contrivance or method of construction which would prevent flexure, would approximate it to this limit. The importance of some

Digitized by Google

such contrivance with thin tubes is thus evident. The necessity for preventing flexure in a column has already been alluded to, and (as in a beam broken transversely) the comparative depth, or leverage with which the material resists flexure, has been shown to be the most important consideration. We may double the width of a plank, and when we stand on the centre, it bends only half as much as before; but if we double its thickness, we have only one-eighth part of its original deflection. It, indeed, assumes another name, and we call it a beam, though in both cases the quantity of material is precisely the same.

18. 'A plate employed as a pillar similarly resists flexure in a much higher ratio than in the simple proportion of its thickness, such stiffness or strength being analogous to the transverse stiffness of a beam. Hence, as in the beam, it will also be highly advantageous to distribute any given material in a pillar in such a manner as to insure the greatest possible depth in the direction in which it is liable to bend. If the pillars are short as compared with their diameter, such precautions are useless, the cubic inch of wrought iron cannot be put in better form; but if it were rolled into a very long and very thin plate one inch broad, and placed on edge, the smallest force would bend it. If we shorten this thin plate by increasing its thickness, but maintaining the same height of one inch, we shall increase its resistance to flexure in proportion directly to the cube of the thickness, and in proportion inversely to the length, since the length will diminish in the same proportion as the thickness increases, therefore the strength will increase directly as the square of the increasing thickness, or inversely as the square of the decreasing length, until the plate arrives at such a thickness that it will fail partly by crushing. The law will now begin to vary as we go on increasing the thickness at the expense of the length; and ultimately, as we approach to the cube itself again, the strength, instead of varying as the square of the increasing thickness, will cease to vary at all with the thickness, its strength will, therefore, have varied during these changes, as every power of the thickness between 0 and the square of the thickness, while the resistance itself would be represented progressively by every quantity between 16 tons and 0, the quantity of material or section and height, having remained constant, so that $n$ square

Digitized by Google

inches of sectional area on the top of a tube may resist any compression between 0 and $n \times 16$ tons, according to the form in which it is applied.

19. 'We should thus use the thickest plates we can get for the top of a tube, until their thickness is such that any variation in the thickness causes no corresponding variation in their resistance to compression—beyond this we get no further advantage. If, however, we are compelled to use thin plates, we should arrange them so as to insure depth to resist buckling. If one cubic inch, when rolled out into a long strip so as as to fail by flexure, were, for instance, formed into corrugations, as in fig. 21, it would in this form support considerably more than in the form

Fig. 21.

of a straight plate, for instead of being a mere line in section with no depth, it would now possess a depth equal to the versed sine of the corrugations, or equal to the distance between each convexity; and in this corrugated form we should attain the maximum resistance to pressure, viz. 16 tons, with our plates much thinner than when used straight. The depth would be still further increased if we folded our corrugated plate round upon itself, so as to complete a series of tubes, fig. 22, taking care to unite carefully the points of contact. There are numberless familiar

Fig. 22.

examples of stiffness obtained by such method of construction. An ordinary paper fan, and many household articles in tin, though constructed of thin and pliable material, are extremely strong and rigid from the depth acquired by the bending of the material. The domestic tea-board and dust-shovel are striking examples. It thus becomes a question, with a given section of material of given thickness, how to construct the strongest form of pillar to resist crushing, and how near we can with this form approach to the limit of 16 tons per square inch.

20. 'Since a flat plate, for the reasons explained, will bend

Digitized by Google

sooner than a curved plate, it would be readily inferred that a round tube, of moderate dimensions and of given thickness and section, would be a stronger form than the same plate in a rectangular form, in which the resistance to crumpling must depend solely on the four angles; and since the rigidity afforded by the angles is extended throughout the four sides of a rectangular tube, in some manner proportionate to the distance from the angles, it would be concluded that a square tube □ would be stronger than a rectangular tube ▭ constructed with the same plate, inasmuch as the central portions of the longer sides of the rectangle will be less maintained in form on account of their greater distance from the angles; similarly increased strength might be expected from this form: ▯▯. These assumptions were all submitted to experiment and confirmed.

'For this purpose a number of tubes or cells of wrought iron were constructed, all 10 feet long and either 4 or 8 inches square, or of rectangular form about 4 × 8 inches; their ends were perfectly flat, and they were compressed by the intervention of a lever between two parallel disks of steel, with arrangements for maintaining the pressure perfectly vertical, the cells being supported laterally. The direct object was to ascertain the value of each particular form of cell, and to ascertain the resistance per square inch of section in each case. The lateral dimensions of these cells were so large, that with a length of 10 feet the pillars were not destroyed by flexure, as in a long pillar, but by absolute buckling or crushing; the strongest possible form should, therefore, give about 16 tons per square inch of section.

21. 'Similar experiments were then made with circular cells under precisely similar circumstances for comparison. The cylinders varying from 1½ to 6 inches in diameter, the diameter being small, in some cases, as compared with the length; some of these pillars failed by flexure, and followed the laws of long pillars, the resistance increasing nearly inversely as the square of the length; but where the diameter was 6 inches, the length being 10 feet, flexure could not take place, and the cells failed by buckling or crushing, as in all the rectangular pillars, and in such pillars the strength is independent of the length.'

Digitized by Google

22. The annexed drawings (figs. 23, 24, 25, 26) show how the failure in the rectangular and cylindrical tubes took place.

From the foregoing researches it will be observed, that in order to determine the maximum powers of resistance to compression in the use of iron plates, the square box with thin plates next to the plate itself is the weakest experimented

Fig. 25.

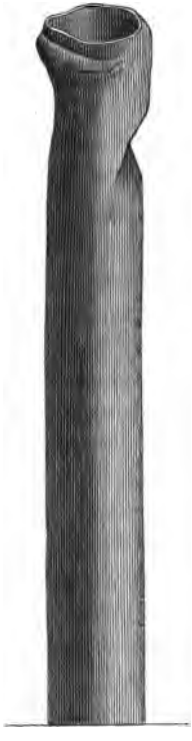


Fig. 23.

Fig. 24.

Fig. 26.

upon; the next in the order of strength is the rectangular form with a division across the centre as at *a*, fig. 24, but the best distribution of the material is in the cylindrical form. This latter cannot, however, be accomplished conveniently in ship building, but the rectangular or cellular construction is applicable in all cases where resistance to compression as well as tension is required in the hull and upper decks of vessels.

Digitized by Google

## CHAPTER V.

### ON THE STRENGTH AND DISTRIBUTION OF THE MATERIAL OF WROUGHT-IRON PLATES AND FRAMES AS APPLIED TO THE CONSTRUCTION OF IRON SHIPS.

1. In this department of inquiry we have not only to consider the nature of the strains to which the sides and other parts of a vessel are subjected, but we have also to determine the distribution of the material in the different parts, so as to establish, as nearly as possible, perfect uniformity of strength. What we mean by uniformity is, that the resistances in any part of the vessel should be proportioned to the strains they have to bear, and that no waste of material should take place beyond what is necessary to maintain the balance of the opposing forces of strain and resistance. In our endeavour to determine the superior value of iron, as a material of which vessels should be constructed, we have not entered into the question of distribution. This is, however, one of the most important elements of construction, and in order to approximate as closely as possible to uniformity of strength, we have to apply the material in such forms and positions as will effectually resist all the various strains to which the vessel is subjected.

2. It will be observed that in the preceding investigation we have invariably viewed the question of vessels, as they are now built, being subject to much severer strains than formerly, when built of wood, and for this reason—that the present class of steamers are nearly double the length that they were formerly as sailing vessels; and the depths are much less in proportion, so as to render their powers of resistance to the action of the sea less than one-half that which would have been the case had the form of construction been upon the old principle. This being the case, a series of strains of double intensity are

Digitized by Google

brought into existence, and these have to be provided for if we are to have safe vessels on the new principle of construction.

All these changes are elements of weakness, unless met by an equable distribution of the material; and it is on this principle that we have treated the new build of vessels as hollow girders. Let us, for example, take a first-rate ship of war as built seventy years ago, such, for instance, as the 'Victory,' and we have:—

| | ft. | in. |
|---|---|---|
| For the length between the perpendiculars . . | 260 | 0 |
| Breadth of beam . . . . . | 60 | 1 |
| Depth . . . . . | 53 | 10 |

This, according to formula $w = \frac{adc}{l}$, would, if built of iron and duly proportioned with a sectional area of 800 square inches for the bottom, and suspended on two points stem and stern, sustain a load in the middle of 9,785 tons, or 19,570 tons equally distributed.

Taking the same sectional area and applying it to a vessel similar to the 'Warrior,' and we have with the same constant 60, and the decks duly proportioned to the bottom,

| | ft. | in. |
|---|---|---|
| For the length . . . . . | 380 | 0 |
| Breadth . . . . . | 58 | 4 |
| Depth . . . . . | 42 | 0 |

Hence $w = \frac{800 \times 42 \times 60}{380} = 5{,}305$ tons as the breaking weight in the middle, or 10,610 tons equally distributed, which is little more than half the strength of the former. From these facts it will be seen that we require an increased sectional area of 675 square inches to balance the resisting forces of the two ships, which evidently shows that, increasing the length and diminishing the depth, as in the present build of vessels, when constructed of the same material, requires an increase of strength in the ratio of 1475 : 800 or as 1 : ·542. But this is not all, as we find from experiment on the effects produced on wrought iron when subjected to alternate changes of load, that to build a durable vessel we should have to proportion the sections of the hull and upper deck, so that, under the varied forms of strains to which she is subjected, no portion of the sectional area shall undergo a strain exceeding five tons per square inch.



Digitized by Google

3. A vessel thus constructed would, in our opinion, be perfectly safe under every condition, when exposed to the action of the sea; but if stranded upon a rock or shelving beach with coal and cargo on board she would be severely tried by the force of impact when continuously rising and falling, under the influence of a tempestuous sea. Even in this precarious position, it is very questionable whether or not she would go to pieces. On the contrary, we are of opinion, if constructed with water-tight bulkheads, strong longitudinal keelsons, and double bottom, that, in nine cases out of ten, she would hold together, and save the lives of all on board.

4. Iron ships, as they are at present constructed, are decidedly defective as regards the distribution of material. The maximum conditions of strength, having the material accumulated at the top and bottom, as in a tubular girder, have not been attended to in their transverse sections, as follows:—

i. The material in this case should be, as far as practicable, accumulated at the top and bottom of the sections at midships, that at the sides being merely sufficient to form a rigid connection between those two parts.

ii. The sectional areas at the top and bottom should be to each other inversely as the ultimate resistances of the material per square inch at the upper and lower edges respectively.

Thus we have the formulæ—

$$w = \frac{4\,s\,a\,d}{l} \quad \text{or} \quad \frac{4\,s_1\,a_1\,d}{l}$$

where the beam is supposed to be supported at each end and loaded in the middle with the weight w, just producing transverse fracture; $d$ = the depth of the beam; $a$ = the area of the top part of the section, s being approximately the ultimate resistance per square inch of the material at the upper edge to extension; $a_1$ = the area of the bottom part of the section; $s_1$ being approximately the ultimate resistance per square inch of the material at the lower edge to compression; and $l$ = the distance between the supports.

From this equality we get—

$$s \cdot a = s_1 \cdot a_1,$$
$$\therefore a : a_1 :: \frac{1}{s} : \frac{1}{s_1}$$

Digitized by Google

5. Now although we cannot distribute the material in the transverse section of an iron ship exactly as it is in a hollow girder of greatest strength, yet the principle should be observed as far as practicable.

Let fig. 5, page 15, represent the transverse section of an iron ship, the various parts being as before described. Now supposing the ship to be supported at its extremities (which is the condition of greatest strain); let M be the moment of its displacement or total weight, tending to rupture the transverse section at the centre; $I_0$ the moment of inertia of the material in this section resisting rupture; and so on, as before, with respect to the other symbols: then, assuming that the compression of wrought iron is equal to the elongation under the same force, we get—

$$M = \frac{s}{h} \cdot I_0 \text{ or } \frac{s_1}{h_1} \cdot I_0$$

Whence we have—

$$\frac{s}{h} = \frac{s_1}{h_1}$$

$$\therefore h : h_1 :: s : s_1$$

That is to say, the material should be so distributed that the distances of the neutral axis from the upper and lower edges should be to each other directly as the ultimate resistances per square inch at these parts respectively. When this condition is fulfilled, the material at the upper edge is upon the point of yielding by compression, whilst the material at the lower edge is upon the point of yielding by extension; but if, for example, the distance of the upper edge from the neutral axis should be greater than what it should be, as determined by this proportion, then rupture would take place at this edge before it would take place at the lower edge.

6. The sectional areas of the material above and below the neutral axis have always a relation to the resistances of the material at those parts—the greater sectional area being always given to that part that presents the least resistance; thus, in the case of wrought iron, the area of the section undergoing compression should exceed that of the section undergoing extension.

7. Taking the ship, referred to at page 15, as a good example



Digitized by Google

of our present mode of construction, and supposing it supported at the extremities, we find the neutral axis to be about $13\frac{1}{2}$ feet from the upper deck, and only about 10 feet from the bottom of the ship. Now when the compressive strain per square inch of the material at the upper edge is 17 tons, the tensile strain per square inch at the bottom edge will be $\frac{17 \times 10}{13\frac{1}{2}}$ or 12·6 tons; but the material at this part is capable of sustaining a tensile strain of about 21 tons per square inch; hence it appears, with this defective distribution of the material, the lower flange is only made to perform about four-sevenths of its duty, or a little more than one-half of what it is capable of performing.* Under such a strain this ship would most certainly be destroyed by fracture at the upper deck, and she would even sustain considerable damage under one-half the strain here brought into play.

8. Now if the upper section of the ship were increased by the addition of about 100 square inches of iron, we should considerably add to the strength of the ship. With this addition to the section of the upper flange, we find that the neutral axis would be 11 feet from the lower flange and $12\frac{1}{2}$ feet from the upper flange; and taking (as Mr. Vernon has done) the maximum moment of force tending to fracture the centre section to be $1{,}800 \times 92\frac{1}{2}$, we find the value of $I_0$ to be 137,300 nearly; that of $s_1$, or the tensile strain per square inch on the bottom edge of the lower flange, to be 13·3 tons; and that of s, or the compressive strain per square inch on the upper edge of the upper flange, to be 15·1 tons. Such a ship might be considerably injured under this maximum strain, but it would be sufficiently strong to resist fracture. It should, however, be borne in mind that although it is *possible* for a ship to be stranded with its extremities only supported, yet it is a circumstance which must very rarely happen.

* This ship, as described by Mr. Vernon, has the following dimensions: Equivalent area top flange, A = 233 square inches; area lower deck, B = 156; area bottom flange, D = 493; area rib representing the two sides of the ship = 440 square inches; depth, A D = $23\frac{1}{2}$ feet; distance between the two decks, A B = $7\frac{1}{2}$ feet; length of the ship 200 feet.

In order to have maximum strength with a given amount of material, the area of the top flange (in a state of tension) should be rather greater than the area of the bottom flange.

Digitized by Google

The distribution of material here assumed almost exactly answers to that of maximum strength when the upper part of the transverse section undergoes a tensile strain, and that of the lower part a compressive strain, which, in fact, is the strain most likely to injure the ship when afloat. For, in this case, the distance of the upper flange from the neutral axis is $12\frac{1}{2}$ feet, while that of the lower flange is 11 feet; and if the ultimate compressive strain per square inch at the lower flange be 17 tons, the tensile strain per square inch upon the upper flange will be $\frac{17 \times 12\frac{1}{2}}{11}$ or 20 tons nearly, which is about the ultimate resistance of wrought iron to extension.

It may not be practicable in all cases to construct iron ships with such a large section of iron at the upper deck, yet such should be the distribution of the material in the section in order to secure a maximum strength with a given amount of material.

9. In the distribution of the material there is another consideration of some importance, and that is, that all bodies in the form of beams, whether hollow or solid, follow the same law as regards a transverse strain, viz., that in a beam uniformly loaded, the strains are always greatest in the middle, and progressively diminish to the points of support at either end. These facts are self-evident, and show, in the case of an iron ship, that the same thickness of plates is not required when working from the centre at midships to the stem and stern. In fact, they should taper or be reduced in thickness according to a certain ratio of their distances from the centre till they reach the extremes at each end.* Theoretically this is

* When a ship is supported at the extremities, and loaded uniformly throughout its length, the moment of the force tending to produce transverse fracture at any point varies as the rectangle of the parts into which this point divides the distance between the two points of support, and the strength of the section at any part should vary according to the same law. In a tubular beam, having its material accumulated at the top and bottom parts of the section, and with a uniform depth, the strength varies as the area of the section, so that, in this case, the area of the section should vary as the rectangle of the parts into which the point (where the section is taken) divides the distance between the supports. If such a beam be divided longitudinally into four equal parts, then the section of the material at the part midway between the centre and the extremity should be three-fourths of the section at the centre. And so on to other cases.

Digitized by Google

true, but in practice we have to consider how much the thickness can be reduced without danger to the structure, and in general we may here observe that the reduction should not exceed *one-third* between the centre and the two extremes. Or, in other words, if we assume the strakes or sheathing plates of the bottom and round the bilge to the height of the interior floor, or one-fifth of the depth, to be seven-eighths of an inch, it then follows that their thickness may be safely and progressively reduced to five-eighths thick towards the bow and stern. The same reduction to five-eighths thick may be made from that point, one-fifth of the depth, to the neutral axis of transverse strains, or about half-way up the ship's side, when they should again increase to seven-eighths thick for the top strakes at the deck, on each side where they have to perform the office of stringers and columns under the action of the two forces of tension and compression.

10. From these remarks, it is obvious that a careful distribution of the material is a condition of considerable importance in ship-building, and although it may be necessary in some constructions to deviate somewhat from the absolute rule, yet it is nevertheless essential that the law of strains should be carefully observed, and weak parts efficiently guarded against.

11. It will not be necessary to give drawings in illustration of these statements, as we apprehend the question to be sufficiently explicit to enable the iron ship builder to proportion the parts in the ratio of the strains, and to afford to the ship, as a whole, ample powers of resistance to the forces by which she may be assailed; care, however, being taken to provide for wear and tear, oxidation, and all those other influences which tend to weaken the ship.

Digitized by Google

# CHAPTER VI.

## THE COMBINATION OF IRON AND WOOD IN THE CONSTRUCTION OF SHIPS.

1. The use of iron, as a material for ship building, suggested several modifications in the construction of ships built entirely of timber. Amongst others was the introduction of iron for the frames and ribs, and to these was screwed the wood sheathing, varying in thickness from four to six inches, according to the size and strength of the ship. This combination was for some time highly appreciated, but, when the properties of the two materials are considered, it will not be difficult to prove that the system is not an eligible one, and, for sea-going ships, is utterly at variance with sound principles of construction. It may be desirable in some cases to have vessels of this construction, such as lake or river boats, but for large ships intended to navigate the open sea, this construction cannot be recommended either on the score of economy or safety.

2. Numbers of these vessels—some of them of large tonnage—have, however, been built; and, in so far as regards fouling, they are superior to the iron-plated ships. As respects strength, they are nevertheless exceedingly defective when compared with those entirely composed of iron. Plate stringers have been introduced, and riveted along the ribs at different parts of the sides, decks, and bottom, but their position has little or no tendency to strengthen vessels of this construction. The following section, figs. 40 and 41, exhibits the principle on which these vessels are constructed, and, comparing this with that of a vessel of similar dimensions composed entirely of iron, we arrive at the conclusion that the method of wood sheathing will scarcely bear a comparison with that of closely riveted iron plates. To prove this, it will be necessary to refer to experiments—1st, upon the comparative strength of iron and wood to a tensile strain; 2nd,

Digitized by Google

upon their comparative resistances to compression; and, lastly, to their comparative powers of resistance to pressure.

TABLE I.—COMPARATIVE VALUES OF IRON AND TIMBER SUBMITTED TO A TENSILE STRAIN.

| Specific Gravities | Description of Timber | Tensile breaking Strain per Square Inch in lbs. | Tensile breaking Strain of wrought Iron per Square Inch in lbs. | Ratio, the Wood representing Unity |
|---|---|---|---|---|
| 7·700 | Wrought iron . . . | 50,000 | 50,000 | |
| 0·560 | Yellow pine . . . . | 12,000 | 50,000 | 1 : 4·16 |
| 0·540 | Cedar . . . . . | 11,400 | 50,000 | 1 : 4·38 |
| 0·580 | Red deal . . . . | 12,500 | 50,000 | 1 : 4·00 |
| 0·640 | Birch . . . . . | 13,000 | 50,000 | 1 : 3·84 |
| 0·660 | Sycamore . . . . | 13,000 | 50,000 | 1 : 3·84 |
| 0·753 | Spanish mahogany . . | 15,000 | 50,000 | 1 : 3·33 |
| 0·780 | Ash . . . . . | 17,000 | 50,000 | 1 : 2·94 |
| 0·700 | Dry English oak . . . | 13,000 | 50,000 | 1 : 3·84 |
| 0·980 | Box . . . . . | 20,000 | 50,000 | 1 : 2·50 |

3. The foregoing table represents the ultimate resistance of the best qualities of iron and timber to a tensile strain, and from which it will be seen, that box and ash stand at the head of the list for strength, and that Spanish mahogany, oak, sycamore, and birch are the next in order, after which red deal or pine—the timber chiefly employed in sheathing ships—is only 500 lbs. per square inch short of the last three. Selecting, however, English oak as the best for comparison, we have the two materials in the ratio of their relative strengths as 1 : 3·84; or, in other words, iron is a little above $3\frac{3}{4}$ times stronger than oak. But in some other experiments, to which we shall hereafter refer, the timber is shown to be not more than one-fifth the strength of iron. These experiments, although bearing directly upon the resisting powers of iron and wood, do not apply to the two materials as ordinarily used in the construction of the sheathing united to the hull and iron frames of ships. To apply the comparison, it must be in the shape of two vessels, one of iron and another of wood, of similar dimensions.

4. The comparative strength of iron and wood, in regard to their respective powers of resistance to a tensile strain, is therefore in the ratio of the strength of the different sorts of timber, as given in the above table. Red pine is probably the best description of timber for sheathing, in combination with iron

Digitized by Google

frames. With 6-inch planking—provided there were no joints, and the ship was covered with a homogeneous mass of jointless timber—it would then be equal to plates of about 1¼ inch thick. But as this is not the case, and as the timber joints are not united, either longitudinally, vertically, or transversely, we must depend on the fastenings to the angle iron ribs, to which the sheathing is bolted, as the only power by which resistance can be offered to strain.

If we carefully examine this construction it will be found, the combined planking being separate from the ribs, that the fracture would be in the direction of the black lines *a a a*,

Fig. 27.

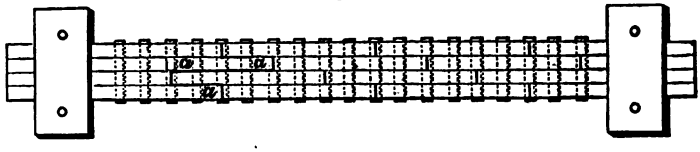


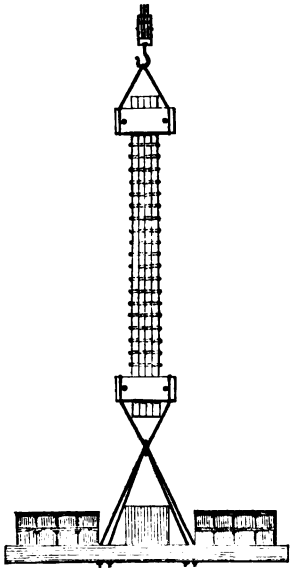
fig. 27, and the tendency would be to separate the end joints and twist the cross ribs, as shown at *c c c*, in fig. 29, and comparing the strengths with iron, as derived from experiment in the following table, it is evident that the strength of vessels of this description, as they are now built, is very inferior to those composed entirely of iron, where the whole of the sheathing, when securely riveted, is homogeneous, and presents greatly increased powers of resistance to every description of strain to which sea-going vessels are subjected.

On this question it will be noticed, that in the iron ship we have the whole of the plates united by rivets in every direction, and to which are secured ribs and frames again united by rivets, forming an unbroken covering of a solid sheet of iron. Now it is well known, from the results of former experiments, that the strength of iron plates riveted in this manner is reduced from 50,000 to 30,000 lbs. per square inch—as in the case of steam boilers—arising from the quantity of iron punched out for the reception of the rivets. This being the case we must reduce the strength of the construction to that proportion. Bearing these facts in mind, we have now to ascertain the strength of the composite form, where the wood sheathing is not united in the joints, but on the contrary is driven asunder

Digitized by Google

by caulking to make it water-tight. In this construction everything is against the strength of the ship; and, in a large sea-going vessel it would be impossible for her to hold together unless united by longitudinal stays and stringers of iron.

Fig. 28.



5. To ascertain the correct value of this construction a platform of wood sheathing of one-sixth the full dimensions was prepared and submitted to the test of experiment. It was composed of red pine, screwed to ribs four inches asunder, representing the frames in a ship in full size of two feet asunder, planking 2 inches by 1 inch, representing sheathing of 6 inches thick, 12 inches wide, and 12 feet long. The whole length of the model was 8 feet, and having attached cross-heads at each end, as shown in the drawing, fig. 28, it was suspended to the jib of a crane, and experimented upon as follows:—

TABLE II.—TENSILE STRENGTH OF TIMBER FRAMES.

Length 8 feet, Ribs 4 inches apart. Joints 2 feet apart. Planking 2 x 1 inches. Sectional area = ·99 x 7·95 inches = 7·87 square inches.

| No. of Experiment | Weight laid on in lbs. | Breaking Strain per Square Inch of Section | | Elongation in Inches | Remarks |
|---|---|---|---|---|---|
| | | lbs. | tons | | |
| 1 | 991 | ... | ... | ·10 | |
| 2 | 1,528 | ... | ... | ·37 | |
| 3 | 1,751 | 222·49 | ·0993 | ... | Broke. |

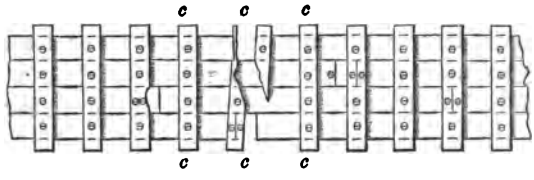
With the first weight, 991 lbs., the joints were slightly separated; with 1,528 lbs. considerable contortion was observed; and with 1,751 lbs. it separated at the joints in the form shown at *a a a*, fig. 27, or on a larger scale at fig. 29.

It is almost superfluous to make the comparison—if the above experiments are to be relied upon—as the disparity is so great as

Digitized by Google

to reduce the strength of a wood-clad ship on iron frames to less than $\frac{1}{130}$ that of the iron one. If, for example, the area of the

Fig. 29.




model be reduced one-fifth, it would then be the representative of 1·57 inch area of iron, which, taken at 30,000 on the square inch, would be 30000 × 1·57=47100 lbs., as the breaking weight at which iron sheathing of that proportion would be torn asunder. Now comparing this with 350·2 lbs., the breaking weight of the model sheathing, and the result is 47100 : 350·2, or as 134·5 : 1; that is, iron is, in this position, 134 times stronger than wood.

In this comparison the sheathing of wood on iron ribs can only act as a water-tight covering attached to iron frames, as the tensile strength of the timber, in the absence of solid transverse joints, contributes only in a very small degree to resist the strains of the ship, and hence arises, in every description of timber-built vessels, the creaking noise and opening of the joints as the vessel plunges and labours in a heavy sea. It is however widely different with an iron-sheathed vessel, as in this case there are no joints, and the whole of the sides and hull present a powerfully resisting force to the strains and motion of the ship.

6. An exclusively timber-built ship has many advantages over that of the composite construction, as the ribs are nearly close together, and when properly fitted with wood or copper fastenings, as practised in Her Majesty's dockyards, the strengths are considerably increased, but still greatly inferior to a properly constructed iron-built ship.

From the extremely limited powers of resistance indicated by the model, it was considered necessary that the tensile strength of the timber, of which it was made, should be tested, but this had no effect on the strength of the platform, as the resistance in the construction does not apply to the timber, but to the pins or fastenings by which they are attached to the ribs. In

Digitized by Google

the case of the model, the screw nails were bent and torn asunder by a comparatively small weight. Doubtless, if the nails had been made double the strength, the results would have been more satisfactory, but the material, whatever it may be, is not calculated from position to meet the force of tension where the joints are numerous and unconnected.

The following tables give the strength of the timber of which the model sheathing was composed :—

TABLE III.—TENSILE STRENGTH OF TIMBER.
Sectional area of timber = ·98 x 1·04 inches = 1·01 square inches.

| No. of Experiment | Weight laid on in lbs. | Breaking Strain per Square Inch of Section | | Elongation in Inches | Remarks |
|---|---|---|---|---|---|
| | | lbs. | tons | | |
| 1 | 653 | ... | ... | | |
| 2 | 1,078 | ... | ... | | |
| 3 | 1,528 | ... | ... | No | |
| 4 | 1,974 | ... | ... | perceptible | |
| 5 | 2,418 | ... | ... | elongation | |
| 6 | 2,920 | ... | ... | | |
| 7 | 3,340 | 3,306 | 1·476 | | Broke |

TABLE IV.—TENSILE STRENGTH OF TIMBER.
Sectional area of Timber = ·98 x 2·00 inches = 1·96 square inches.

| No. of Experiment | Weight laid on in lbs. | Breaking Strain per Square Inch of Section | | Elongation in Inches | Remarks |
|---|---|---|---|---|---|
| | | lbs. | tons | | |
| 1 | 3,340 | ... | ... | | |
| 2 | 4,288 | ... | ... | | |
| 3 | 4,709 | ... | ... | | |
| 4 | 5,132 | ... | ... | No | |
| 5 | 5,625 | ... | ... | perceptible | |
| 6 | 6,089 | ... | ... | elongation | |
| 7 | 6,509 | ... | ... | | |
| 8 | 6,949 | ... | ... | | |
| 9 | 7,432 | 3,791 | 1·692 | | Broke |

Digitized by Google

7. To show the value of iron constructions as compared with those in combination with wood as exhibited in section figs. 40 and 41, it may be instructive to insert an extract from the experiments of 1838, or that part of them which relates to the resistance of wrought-iron plates and different sorts of timber to pressure, by a blunt hemispherical instrument, at right angles to the surface.

Irrespective of the experiments made to determine the strength of wrought-iron plates and the relative strength of the joints by which they are united, the investigation would be incomplete if we omitted another inquiry of equal importance, namely, the resistance offered by plates to a crushing force, such as exhibited in the injuries received by vessels when stranded on rocks or taking the ground in harbours where the surfaces are uneven.

Almost every person connected with nautical affairs is acquainted with the nature of the injuries received by timber-built vessels when placed in circumstances affecting their stability, or when resting on hard and unequal ground, such as frequently occurs in tidal harbours at low water. Such a position is attended with danger under every circumstance; and in order to determine the relative values of the two materials, wood and iron, it was considered desirable to institute a similar class of experiments on both, and thus to afford the means of comparison between them. English oak, as the strongest and best material used for the construction of first-class wooden vessels, was selected for this purpose, and the results obtained from both are given, under circumstances as nearly similar as the nature of the experiment would admit. They are as follows:—

8. In each of the experiments the plate was fastened upon a frame of cast iron, 1 foot square inside and 1 foot 6 inches outside, its breadth being 3 inches and thickness half an inch. The sides of the plates, when hot, were twisted round the frame, to which they were firmly bolted. The contraction, by cooling, caused it to be very tight, and the force to burst it was applied in the centre. This was done in order that the force might in some degree resemble that from a stone or other body with a blunt end pressing against the side or bottom of a vessel: a bolt of iron, terminating in a hemisphere 3 inches in diameter, had

Digitized by Google

thus its rounded end pressed perpendicularly to the plate in the middle. The results are given in the following tables:—

TABLE V.—EXPERIMENTS TO DETERMINE THE RESISTANCE OF PLATES OF WROUGHT IRON TO A FORCE TENDING TO BURST THEM.

| No. of Experiment | Description of Plates | Weight laid on in lbs. | Permanent Indentation of Plate | Remarks |
|---|---|---|---|---|
| | | | inch | |
| 1. | Plate of the best Staffordshire iron ¼ inch thick. | 8,617 | ·3 | Plate not cracked. |
| | | 9,893 | ·35 | Plate not cracked. |
| | | 11,169 | ·5 | Crack on convex side 8 inches long. |
| | | 12,445 | ·6 | Crack on convex side 9 inches long; not opened on concave side. |
| | | 13,789 | ·7 | Hole through the plate about 1½ inch long, and ⅛ inch wide. |
| 2. | Plate of the same iron and the same thickness. | 9,893 | ·25 | Double crack on convex side 1 inch long. |
| | | 11,169 | ·34 | Double crack increased. |
| | | 12,445 | ·4 | |
| | | 13,789 | ·47 | |
| | | 16,477 | ·6 | Form of crack on convex side (⅛ inch wide). |
| | | 17,821 | ·65 | Not cracked through. |
| | | 19,769 | ... | Cracked through. |
| 3. | Plate of the same iron ½ inch thick. | 18,523 | ... | No crack. |
| | | 21,075 | ·33 | Incipient crack on convex side. |
| | | 22,787 | ·45 | Crack above-mentioned 4 inches long forming a cross. |
| | | 25,923 | ·60 | Crack above, 6 inches long. |
| | | 29,059 | ·75 | Crack above, ⅛ inch wide. |
| | | 32,195 | ·80 | |
| | | 35,331 | ·97 | |
| | | 36,899 | 1·10 | No crack on concave side. |
| | | 37,519 | ... | Plate cracked through. |
| 4. | Plate same as the last. | 21,219 | ... | No crack. |
| | | 21,985 | ·35 | Slight crack on convex side. |
| | | 27,708 | ·47 | Form of crack on convex side. |
| | | 31,796 | ·7 | Form of crack increased. |
| | | 33,431 | ·75 | |
| | | 35,066 | ·83 | Form of crack 4 inches deep. |
| | | 36,701 | ·97 | Not cracked through. |
| | | 37,928 | ... | Cracked through. |

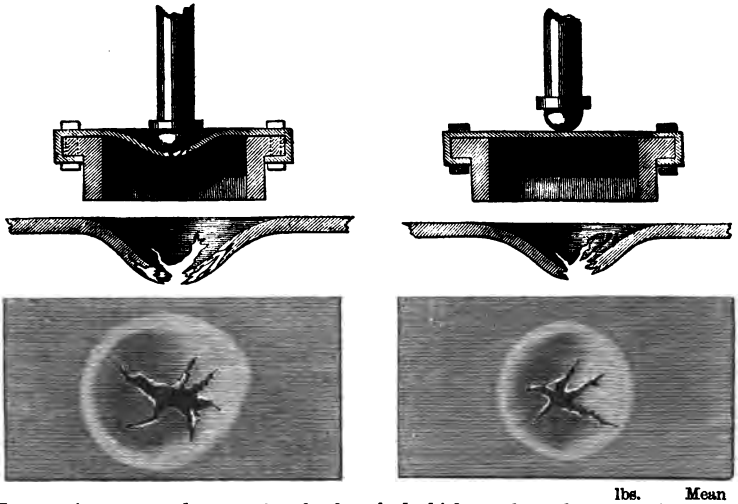
In figs. 30 and 31 will be found representations of the fractures of the plates experimented upon.

From the above we obtain the strength of plates to resist

Digitized by Google

rupture from pressure from a blunt body, or a ball 3 inches diameter.

Figs. 30, 31.



| | lbs. | Mean |
|---|---|---|
| In experiment 1, a plate one-fourth of an inch thick was burst by | 13,789 | 16,779 |
| In experiment 2, a plate one-fourth of an inch thick was burst by | 19,769 | |
| In experiment 3, a plate half an inch thick was burst by . . | 37,519 | 37,723 |
| In experiment 4, a plate half an inch thick was burst by . . | 37,928 | |

Here the strengths are as the depths, a half-inch plate requiring double the weight to produce fracture that had previously burst the quarter of an inch plate. In the succeeding experiments on oak timber, the powers of resistance follow the ratio of the squares of the depth, so that a wrought-iron plate of only one-quarter of an inch thick is able to resist a force equal to that required in the rupture of a 3-inch plank.

9. The experiments were made upon good English oak, of different thicknesses, and of the same width as the iron plates. The specimens were laid upon solid planks, 12 inches asunder, and by the same apparatus the rounded end of the 3-inch pin was forced through them as follows :—

Resistance of planks of timber to the entrance of a ball, 3 inches diameter, the planks being laid upon props 12 inches asunder; the object of the experiments being to burst them by pressing a pin, terminated by a hemispherical end, 3 inches diameter, through the centre of the plank, as was done with the plates of iron.

Digitized by Google

TABLE VI.

| No. of Experiment | Description of Plank | Weight laid on | Remarks |
|---|---|---|---|
| 1. | English oak, very dry and good, 11¾ inches broad, and 2½ inches deep. | lbs. 16,115<br>17,235 | Indentation from hemisphere ½ inch deep; wood otherwise uninjured.<br>Hole through the middle, 3 inches diameter nearly broke out, all the rest remaining sound. |
| 2. | English oak, rather green, 8 inches broad, 3 inches deep. | 18,941 | It bore 18,941 lbs. about ten minutes, and then exploded with violence, dividing into three parts, the middle one on which the pin rested being about an inch thick at the top, and half an inch at the bottom. With a ton less weight there was a crack under the plank in the centre, and an indentation by the pin ½ inch deep on the upper side. Sap was driven out from the ends on the side nearest to the heart. |
| 3. | English oak plank, and dimensions same as in last experiment. | 12,445<br>16,925 | Sap driven out as in last experiment; plank without crack; indentation by the pressure about ½ inch.<br>The plank split with bearing the pressure about ten minutes. |
| 4. | English oak from same plank as in experiments 2 and 3; breadth 8 inches, depth 1½ inch. | 4,532 | The plank broke by splitting. |
| 5. | English oak from same plank and same size as in the last experiment. | 4,280 | Broke by splitting diagonally. |

Taking the results of the four last experiments, which were on pieces from the same plank, we obtain—

| | lbs. | Mean |
|---|---|---|
| Strength from planks 3 inches thick . . . | 18,941 | 17,933 |
| Strength from planks 3 inches thick . . . | 16,925 | |
| Strength from planks 1½ inch thick . . . | 4,532 | 4,406 |
| Strength from planks 1½ inch thick . . . | 4,280 | |

Here the strength to resist crushing follows the ratio of the square of the depth, as is found to be the case in the transverse fracture of rectangular bodies of constant breadth and span.

10. If we compare the foregoing results with the experiments performed by Mr. Hodgkinson on timber, it will be found that

Digitized by Google

the strength of dry English oak to resist a crushing force is 4·24 tons to the square inch, whereas wrought iron, according to Rondelet, requires a pressure of about 31 tons per square inch, and with this weight it is reduced about one-sixteenth of its length. The resistance of wrought iron to a crushing force is therefore about seven and a quarter times greater than that of oak: and according to the experiments in the preceding Table, it appears that the resistance of wrought-iron plates to a force calculated to burst them follows a different law to that of oak, the resistance of the former being directly as the depth and of the latter as the square of the depth. Reasoning from these facts, it may be interesting to know that in the use of timber, such as the oak sheathing of ships, the strength to external pressure increases in the ratio of the squares of its thickness; and, where great strength is required, it will be necessary, in the construction of vessels, to consider the nature of the service and the required thickness of the planks.

11. The same remarks will apply to vessels constructed of iron, computed from the formula deduced from the experiments. In a table of experimental results by Mr. Hodgkinson we have the mean force per square inch required for crushing timber of different kinds; and assuming Rondelet's experiments, which give 70,000 lbs. as the resistance per square inch of wrought iron, to be correct, we then have as the ratio of their respective powers of resistance as follows:—

TABLE VII.—COMPARATIVE STRENGTH OF IRON AND TIMBER UNDER A COMPRESSIVE STRAIN.

| Specific Gravities | Description of Timber used | Resistance per Square Inch | Resistance of Wrought Iron per Square Inch | Ratio, the Wood representing Unity |
|---|---|---|---|---|
| | | lbs. | lbs. | |
| 7·700 | Wrought iron . . | ... | 70,000 | |
| 0·560 | Yellow pine . . | 5,375 | 70,000 | 1 : 13·02 |
| 0·540 | Cedar . . . . | 5,674 | 70,000 | 1 : 12·33 |
| 0·580 | Red deal . . . | 5,748 | 70,000 | 1 : 12·16 |
| 0·640 | Birch . . . . | 6,402 | 70,000 | 1 : 10·93 |
| 0·660 | Sycamore . . . | 7,082 | 70,000 | 1 : 9·88 |
| 0·753 | Spanish mahogany . | 8,198 | 70,000 | 1 : 8·53 |
| 0·780 | Ash . . . . . | 8,683 | 70,000 | 1 : 8·06 |
| 0·700 | Dry English oak . . | 9,509 | 70,000 | 1 : 7·36 |
| 0·980 | Box . . . . . | 9,771 | 70,000 | 1 : 7·16 |

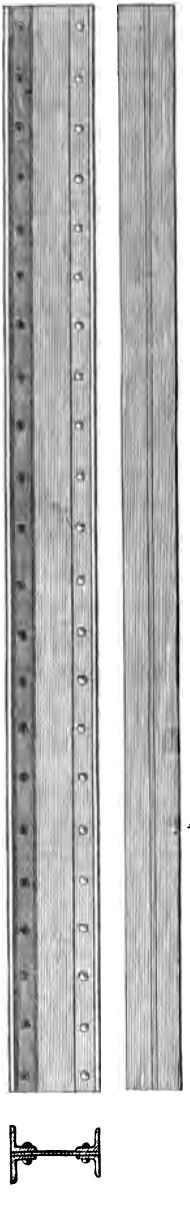
In addition to the relative resisting forces of the different



Digitized by Google

kinds of timber above enumerated, will be found the specific gravity of each, which enables the reader to determine the comparative weights as well as strength of the different kinds of wood.

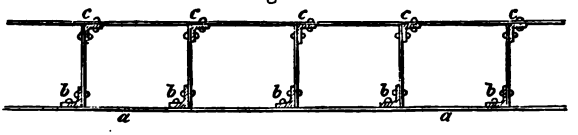
Fig. 32.



*Frames and Ribs of Iron Ships.*

12. In the preceding researches I have endeavoured to determine the value of iron chiefly in reference to its application for the purposes of ship building. It now only remains to determine the best form and condition of another part of the structure, namely the frames and ribs of vessels, also composed of iron. Some of the forms experimented upon indicate weakness, but certain modifications which have since been introduced have given increased support to the bilge and sides of the ship, and greater powers of resistance to the outer sheathing. The beam shown in fig. 32 is probably one of the strongest and most suitable for the support of the deck, but it is inadmissible as a frame for receiving the exterior sheathing plates. These frames are generally formed of a plate with angle-irons along the edges on both sides, of

Fig. 33.



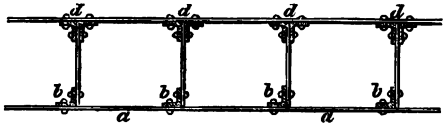

which the annexed sketch, fig. 33, is a section. *a*, *a*, &c., represents a portion of the outside plates; *b*, *b*, the angle-iron frames or frame ribs, which vary from 18 to 24 inches asunder, according to the position in the direction of the length of the ship; *c*, *c*, angle-iron of the same strength is riveted along the edge of each rib for the purpose of stiffening the sides of the ship and for giving increased resistance to those parts, also to receive interior plates, some of

Digitized by Google

which, in large vessels, are riveted diagonally to the interior angle-irons, *c*, *c*, &c., forming stringers and braces from the keelsons round the bilge to the upper decks.

13. Other kinds of frames might be used with double angle-iron, as shown at *d*, *d*, &c., in the annexed sketch, but they are

Fig. 34.




more expensive, and from the increased complexity of construction, the extra strength obtained does not compensate for the difference of cost. Altogether, the frames recorded in fig. 33 have come into general use as the most effective and easy of construction. Those experimented upon were of different kinds, as shown in figs. 32, 35, 36, 37, and 38, and in sections given in the tables, and from which the following results were obtained:—

Fig. 35.

Beam before the experiment, rib downwards. Weight of beam 54lbs.

Beam after the experiment.

Beam showing the flange rib downwards.

Fig. 36.

Beam before the experiment, rib upwards. Weight of beam 55lbs.

Beam after the experiment.

Digitized by Google

Plan of beam before the experiment.

Beam after the experiment.

Fig. 37.

Beam before the experiment, rib downwards. Weight of beam 82½lbs.

Beam after the experiment.

Beam with the flange downwards.

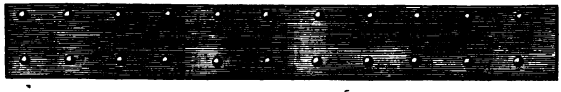


Fig. 38.

Beam before the experiment, rib upwards. Weight of beam 85lbs.

Beam after the experiment.

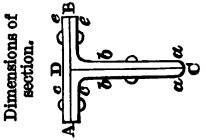
Plan of beam before the experiment.

Beam after the experiment.

Section of the beams.

Digitized by Google

TABLE VIII.—EXPERIMENTS TO ASCERTAIN THE STRENGTHS OF UNIFORM WROUGHT-IRON BEAMS OF DIFFERENT FORMS TO SUPPORT THE SIDES AND OTHER PARTS OF VESSELS, THE BEAMS HAVING THEIR ENDS PLACED UPON PROPS AND BEING LOADED IN THE MIDDLE.

| No. of Experiment | Description and Form of the Beam | Weight laid on Middle | Deflections with these Weights | Breaking Weight of the Beam of 7 ft. between the Supports | Weight of the Beam of 7 ft. 6 in. long | Oak Beams: Side of Square of Oak Beams of equal Strength with the Iron one | Oak Beams: Weight of such Beams of 7 ft. 6 in. long and Specific Gravity 900 | Remarks |
|---|---|---|---|---|---|---|---|---|
| 1 | Beam formed from two 2½ angle-irons, riveted together with rivets 6 inches asunder, and a plate a ¼-inch thick riveted to the back, with rivets 4 inches asunder. Distance between the supports 7 feet, and whole length 7 feet 6 inches, its weight being 109 lbs.  Dimensions of section. Thickness. AB = 5 inches. CD = 2·6 inches. *aa* = ·5 inch. *bb* = ·56 inch. *cc* = ·64 inch. *ee* = ·25 inch. The part C was downwards during the experiment, the weight being laid upon the part D. | lbs. | | lbs. 3,355 | lbs. 109 | inches 3·6324 | lbs. 38·65 | The weight 3,355 lbs. was laid on at once, and the beam almost immediately sunk with it; a weight something less would have done it. |
| 2 | The beam last used, cut in two; distance between the supports 2 feet 3 inches; vertical rib downwards, that it might be stretched as before; weight of 3 feet 9 inches = 54 lbs. | 4,039<br>5,383<br>6,055<br>6,727<br>7,399<br>7,735 sunk | ·18<br>·30<br>·43<br>·64<br>·88<br>.. | 2,486 | 109 | 3·287 | 31·80 | With 7,735 lbs. it sunk, by stretching and tearing at a rivet-hole. |
| 3 | The other half of the beam (Exp. 1) cut in two. Distance between the supports 2 feet 3 inches; weight of 3 feet 9 inches = 55 lbs.; vertical rib upwards thus, ⊥ that fracture might take place by the compression of that rib. | 4,039<br>5,383<br>6,055<br>6,727<br>7,399<br>8,071<br>8,743<br>9,415<br>10,087<br>10,423<br>10,759 sunk | ·17<br>·23<br>·26<br>·34<br>·47<br>·63<br>·85<br>1·10<br>1·95<br>2·90<br>.. | 3,458 | 109 | 3·6692 | 39·44 | With 10,759 lbs. it sunk; the vertical rib becoming twisted. |

Digitized by Google

TABLE IX.—EXPERIMENTS ON WROUGHT-IRON BEAMS—(*continued*).

| No. of Experiment | Description and Form of the Beam | Weight laid on Middle | Deflections with these Weights | Breaking Weight of the Beam of 7 feet between the Supports | Weight of the Beam of 7 feet 6 inches long | Oak Beams: Side of Square of Oak Beams of equal Strength with the Iron one | Oak Beams: Weight of such Beams of 7 feet 6 inches long and Specific Gravity 900 | Remarks |
|---|---|---|---|---|---|---|---|---|
| | | lbs. | | lbs. | lbs. | inches | lbs. | |
| 4 | Beam differing from that in Exp. 1 only in being of greater strength, this beam being formed of two 3-inch angle-irons, riveted as before to a plate a ¼-inch thick. Distance between the supports 7 feet; weight of the beam 7 feet 6 inches long, 167½ lbs.; vertical rib downwards T. | 3,355 | ·40 | | | | | After bearing the weight 7,399 lbs. a short time the beam became cracked at a rivet-hole and sunk. From the experiments of Buffon upon green oak, the side of a square beam of equal strength would be 4·558 inches, and its weight 708 lbs. |
| | | 4,711 | ·62 | | | | | |
| | | 5,383 | ·82 | | | | | |
| | | 5,719 | ·98 | | | | | |
| | | 6,055 | 1·12 | | | | | |
| | | 6,391 | 1·30 | | | | | |
| | | 6,727 | 1·87 | | | | | |
| | | .. | 1·92 | | | | | |
| | | 7,063 | 2·29 | | | | | |
| | | 7,399 | 3·25 | 7,399 | 167·5 | 4·7281 | 65·49 | |
| 5 | Half the beam used in Exp. 4, now 3 feet 9 inches long, and weighing 82½ lbs. Distance between supports 3 feet 6 inches; vertical rib downwards. | 4,039 | 0·85 | | | | | |
| | | 7,399 | 0·25 | | | | | |
| | | 10,759 | 0·43 | | | | | |
| | | 11,431 | 0·53 | | | | | |
| | | 12,103 | 0·65 | | | | | |
| | | 12,439 | broke at a rivet-hole. | 6,219 | 1,675 | 4·462 | | |
| 6 | The other half of the beam in Exp. 4, weighing 85lbs.; length 3 feet 6 inches. Distance between the supports 2 feet 3 inches; rib upwards ⊥. | 8,304 | 0·12 | | | | | |
| | | 12,392 | 0·24 | | | | | |
| | | 16,480 | 0·75 | | | | | |
| | | 18,115 | sunk, the vertical rib being twisted. | 5,823 | 1,675 | 4·3653 | 55·83 | |

Digitized by Google

All the beams experimented upon in Table VIII. are shown in view and in section, figs. 35, 36, 37, and 38. In the first experiment the beam was 7 feet between the supports, but having yielded to the first weight, 3,355 lbs., laid on, it was subsequently cut in two. In experiment 2, it will be observed that a frame of this form is weak, arising from the deficiency of material on the lower side of the rib formed by angle-iron, which, yielding to a tensile strain, becomes elongated in the act of bending, and would thus deflect through a considerable space before actual fracture took place. Reversing the other part of the beam with the broad flange downwards it carried more weight, but ultimately sunk under a load of 10,759 lbs., being in the ratio of 10 : 7 in favour of the beam with the rib upwards.

These experiments, when reduced to 7 feet between the supports, gave nearly the same proportion, viz. nearly as 34 : 24. They are however all weak, arising almost exclusively from want of material on the top edge of the ribs, and a due proportion in the construction of the beam.

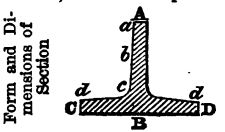
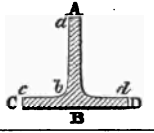
The whole of the experiments recorded in Table IX. are of the same description as the last, with the exception of the beam being composed of thicker angle-iron, and consequently rendered much stiffer and stronger than those first experimented upon. This increased stiffness reversed the resisting powers of the beam, when taken at a 7-feet span, in the ratio of 6 : 5 in favour of the first position with the rib downwards. For plans and sections of these beams see fig. 38.

The experiments in Table X., page 88, were made on solid T iron, and indicate nearly the same proportions, as respects their strength, as the beams composed of a plate and double angle-iron riveted together. The whole of these beams appear to be defective in form, and are therefore not calculated to sustain a severe transverse strain. To attain the section of greatest strength, it is probable a different form would be required, as well as a different proportion of the parts, such as in the annexed figure with a double flange.* (See exp. 11, p. 89.)

* Since the experiments herein recorded were made, others have been instituted on some deck-beams by Mr. Kennedy of Messrs. Bury, Curtis and Kennedy, Liverpool, the particulars of which are inserted in the Appendix of 'Useful Information for Engineers,' 4th edition, p. 318, *et sequitur*.

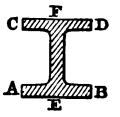
Digitized by Google

TABLE X.—EXPERIMENTS ON WROUGHT-IRON BEAMS—(*continued*).

| No. of Experiment | Description and Form of the Beam | Weight laid on Middle | Deflections with these Weights | Breaking Weight of the Beam of 7 ft. between the Supports | Weight of the Beam of 7 ft. 6 in. long | Oak Beams: Side of Square of Oak Beams of equal Strength with the Iron one | Oak Beams: Weight of such Beams of 7 ft. 6 in. long and Specific Gravity 900 | Remarks |
|---|---|---|---|---|---|---|---|---|
| 7 | Solid wrought-iron beam, 4 feet 2 inches long, weighing 23 lbs., placed upon props 4 feet asunder; vertical rib upwards. Form and Dimensions of Section   Thickness at $a$ = ·24, $b$ = ·29, $c$ = ·41, $d$ = ·36, AB = 2·50, CD = 2·85 | lbs.<br>1,394<br>1,932<br>2,470<br>2,739<br>3,008 | ·135<br>·24<br>·59<br>·90<br>1·35 | lbs.<br>1,790 | lbs.<br>41·4 | inches<br>2·9461 | lbs.<br>25·43 | With 3,008 lbs. the elasticity was entirely destroyed, and a like additional weight would have destroyed the form of the beam. |
| 8 | Same beam rendered straight, and turned with its rib downwards T. | 1,394<br>1,932<br>2,470<br>2,739<br>3,008<br>3,423 | ·17<br>·25<br>·66<br>1·22<br>2·20<br>sunk | 1,870 | 41·4 | 2·9894 | 26·18 | |
| 9 | Solid beam, same form as before; length 5 ft. 8 in.; weight 25½ lbs. Distance between supports 4 ft.; rib upwards thus. See fig. to experiment 7.   Thickness at $a$ = ·23, $b$ = ·30, $c$ = ·40, $d$ = ·33, AB = 2·05, CD = 2·95 | 1,394<br>1,932<br>1,526<br>2,201<br>2,335<br>2,335 in a few minutes | ·30<br>·86<br>1·19<br>1·59<br>2·04<br>2·13 | 1,334 | 37·6 | 2·671 | 20·90 | After bearing the weight, 2,335 lbs., it had taken a permanent set or flexure = 1·71 inch, and would have sunk more if it had not been unloaded. |
| 10 | Same beam rendered straight and turned upside down, thus T. Distance between supports 4 feet. | 1,394<br>1,932<br>2,201<br>2,335<br>2,335 in a minute<br>2,469 | ·27<br>·51<br>1·01<br>1·57<br>1·60<br>2·50<br>.. | 1,411 | 37·6 | 2·7215 | 21·70 | After bearing 2,469 lbs. it was unloaded, as a little additional weight would have destroyed its form. |

Digitized by Google

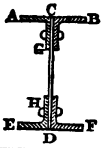
TABLE XI.—EXPERIMENTS ON WROUGHT-IRON BEAMS—(*continued*).

| No. of Experiment | Description and Form of the Beam | Weight laid on Middle | Deflections with these Weights | Breaking Weight of the Beam of 7 feet between the Supports | Weight of the Beam of 7 feet 6 inches long | Oak Beams: Side of Square of Oak Beams of equal Strength with the Iron one | Oak Beams: Weight of such Beams of 7 feet 6 inches long and Specific Gravity 900 | Remarks |
|---|---|---|---|---|---|---|---|---|
| 11 | Beam of wrought iron, formed of two bars (nearly equal), whose section is riveted together; length of the beam 4 feet 2 inches; its weight 44 lbs. 5 oz. Distance between the supports 4 feet.<br>Dimensions of Section<br>AB = 2·86 inches.<br>Mean thickness of<br>AB = ·33 inch.<br>EF = 3·70 inches.<br>  <br> | lbs.<br>4,195<br>7,465<br>10,735<br>10,735 laid on again.<br>14,005 | 0·75<br>0·148<br>0·22<br>..<br>0·24 broke | lbs.<br>..<br>8,336 | lbs.<br>..<br>79·76 | lbs.<br>..<br>4·9199 | lbs.<br>..<br>70·91 | After bearing the weight 10,735 lbs., the beam had taken a set=·06. Pieces of wood were driven tightly in between the ribs AB, CD, at each side of the beam in *the middle*, to prevent the load laid on it there from deranging its form. The beam broke by the bottom rib being torn asunder, preceded by one of the bars cracking at a rivet-hole. |

The above is probably the strongest form of beam, if duly proportioned, by adapting the material to a balance of the two opposing forces of extension and compression.

Digitized by Google

TABLE XII.—EXPERIMENTS ON WROUGHT-IRON BEAMS—(*continued*).

| No. of Experiment | Description and Form of the Beam | Weight laid on Middle | Deflections with these Weights | Breaking Weight of the Beam of 7 feet between the Supports | Weight of the Beam of 7 feet 6 inches long | Oak Beams: Side of Square of Oak Beams of equal Strength with the Iron one | Oak Beams: Weight of such Beams of 7 feet 6 inches long and Specific Gravity 900 | Remarks |
|---|---|---|---|---|---|---|---|---|
| 12 | Beam of wrought iron composed of a uniform vertical rib (7 inches deep and 7 feet 6 inches long) with two 2-inch angle-irons riveted to both top and bottom of the rib; rivets 4 inches asunder; weight of beam 161½ lbs. Distance between the supports 7 feet.<br>Dimensions of Section.<br>CD = 7 inches.<br>AB = 4·5 inches.<br>EF = 4·5 inches.<br>Mean thickness of<br>AB = ·28 inch.<br>EF = ·30 inch.<br>Plate GH = ·25.<br>  <br> | lbs.<br>4,216<br>8,304<br>16,480<br>18,667<br>22,027<br>in five minutes<br>24,379 | ·10<br>·18<br>·25<br>·36<br>·52<br>·54<br>sunk | lbs.<br>24,379 | lbs.<br>161½ | inches<br>7·0358 | lbs.<br>145·03 | With the weight 24,379 lbs. the top ribs of the beam became twisted. |
| 13 | Same beam rendered straight and uniform; experiment 12 repeated. | 16,115<br>18,355<br>19,475<br>20,595<br>21,715 | ·29<br>·36<br>·42<br>·51<br>sunk | 21,715 | 161½ | 6·7695 | 134·26 | The beam was heated by the smiths, and when reduced to its original form, it was allowed to cool gradually.<br>With 21,715 lbs. it became bent, towards the wall, in a direction in which it was slightly drawn by the lever; ribs not twisted as before. It bore the weight a minute or two before giving way. |

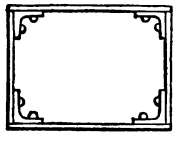
Digitized by Google

This experiment shows the superior quality of wrought-iron beams in giving timely notice before fracture; it further exhibits weakness on the top sides of the beams, a circumstance requiring great attention in their construction, which in some recent experiments, instituted for attaining the section of greatest strength, has been strikingly developed.*

14. In the preceding experiments, we have endeavoured to compare the strength, as well as the weight of the beams or frames which form the ribs of ships. As regards the strengths with equal weights, it is in favour of oak; but the circumstance of the fastenings by rivets in the sheathing being so much superior to those of timber, the iron ship builder is enabled to dispense with one-half the number of frames, and consequently a great reduction of weight is effected and more strength obtained in the vessel as a whole, than could possibly be accomplished in the timber-built ship, however ingenious the construction or the arrangement and distribution of the material. The very act of caulking the joints of a wooden vessel has a tendency to loosen the fastenings, whereas, in the iron ship, there are no actual joints, for the whole being bound together *en masse*, the same, or nearly the same, strength is obtained as if the whole ship were composed of solid plates and ribs.

15. The best sectional form of beams for the decks of ships is probably that exhibited in Table XII., which, along with the box beam of the annexed form, fig. 39, for supporting the shafts and paddle-boxes of steamers, is that generally used in the construction of vessels of this description. Other forms have been adopted, particularly those suggested by Mr. Kennedy of Liverpool, alluded to in the appendix of 'Useful Information.'

Fig. 39.



16. Having carefully investigated the different properties of wrought iron in its varied forms of construction, and conceiving that the results obtained from the experiments may be useful in a variety of circumstances connected with the useful arts, I have endeavoured to collect them in the abstract, in order that the practical builder and engineer may the more readily ascertain

* See the Author's work on the construction of the Britannia and Conway Tubular Bridges.

Digitized by Google

the comparative value of the different forms of beams, the properties of the material, and their adaptation to any particular construction in which he may be engaged. Should further information be required, we must then refer to the experiments, in which will be found the facts more in detail, and which are probably better calculated to satisfy the inquiring mind and to effect that conviction essential to success.

17. I have not attempted any inquiry into the laws of oxidation, the adhesion of barnacles and marine vegetation, and the means necessary to prevent such evils. This is a subject which does not come within the province of the present inquiry, and more properly belongs to that of the chemist. I would however briefly notice, that in the whole of my experience I have had little to complain of from the effects of oxidation, as that destructive process, as regards iron, appears to be greatly mitigated, if not almost suspended, by constant use, and under the influence of vibration the chemical action appears to be rendered nugatory, if it does not entirely cease, and that under circumstances exceedingly difficult to explain. This is an investigation not unworthy the attention of our best chemists, to whom the causes may be known, but which are at present, as far as I know, unaccounted for. For example, I may mention that an iron ship, if kept constantly in use, or nearly so, will last for a number of years exposed to all the changes of weather and temperature without any sensible appearance of decay. The same may be said of iron rails, over which are passing daily such enormous weights, and at such velocities as almost to neutralise the action of the atmosphere. All these are striking examples of the durability of wrought iron, which may be considered an important element of its security, and a recommendation for its extended application. There is another circumstance in connection with this subject to which it may be necessary in this place to advert, and that is the effect which a long continuance in salt water has upon the hull of an iron ship. It is well known that a long immersion of cast iron in the sea will convert it into plumbago, and that a similar process with malleable iron, from its contact with the saline particles of the ocean, produces oxidation; and in case the immersions were long continued, the effects of this destructive process might

Digitized by Google

endanger the safety of the ship. As yet we have not had sufficient evidence of its effects to enable us to come to any definite conclusion, but it is not improbable that an occasional visit to harbours of fresh water may mitigate, if it does not entirely neutralise, the injurious effects which the material is likely to sustain. With these observations, which I offer with diffidence, I now beg to direct attention to the abstract deduced from the experiments.*

*Abstract of Results obtained from the experiments.*

18. In the first part of this inquiry we have endeavoured to show that 50,000 lbs. per square inch is the mean breaking weight of iron plates, whether torn asunder in the direction of the fibre or across it (see page 72); that the tensile strength of different kinds of timber drawn in the direction of the fibre varies in a given ratio to that of iron; and we have also assumed 70,000 lbs. as the resistance of wrought iron per square inch to a crushing force to be correct: the timber in this comparison being represented by unity, we have the following ratio of strength:—

| | Timber | | Iron | | | Timber | | Iron | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ash as . | . 1 | : | 2·94 | for tension, | and | 1 | : | 7·77 | for compression. | |
| Teak as | . 1 | : | 3·33 | „ | „ | 1 | : | 5·83 | „ | „ |
| Fir as . | . 1 | : | 4·16 | „ | „ | 1 | : | 13·02 | „ | „ |
| Beech as | . 1 | : | 4·34 | „ | „ | 1 | : | 7·47 | „ | „ |
| Oak as . | . 1 | : | 5·00 | „ | „ | 1 | : | 7·00 | „ | „ |
| | &c. | | | &c. | | | | &c. | | |

These, for practical purposes, may be taken as a fair measure of the strength of the different woods as compared with that of iron plates.

With reference to the relative resistance of plates and timber to the vertical pressure of a blunt instrument forced through them, for the purpose of ascertaining their comparative powers of resistance when placed under circumstances precisely similar, and subjected to the same force, we observe that the results will be found interesting, inasmuch as the iron plates appear to follow a different law in their resistance to pressure to that of

* For the mathematical formulæ relative to the beams in the foregoing experiments, *vide* Philosophical Transactions, 1850, and 'Useful Information for Engineers,' 4th edition, p. 304, *et sequitur*.

Digitized by Google

Fig. 41.

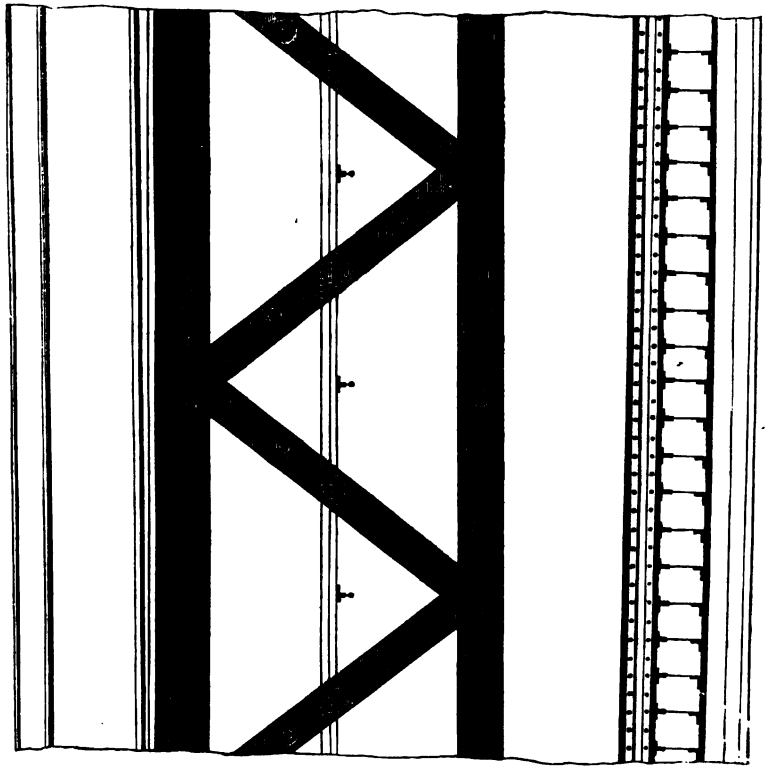
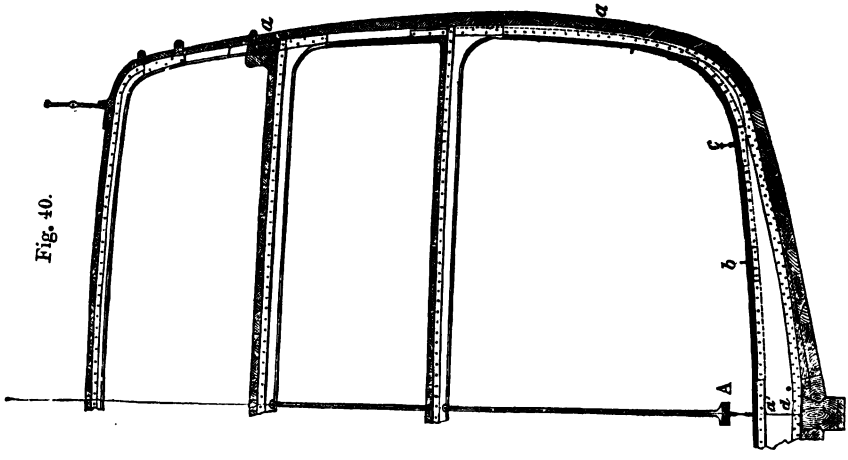


Fig. 40.




Digitized by Google

oak, the strength being as the depth or thickness of the plates in the first case, and as the squares of the depth in the second. The resistances are therefore in the ratio of 1 : 12, the iron being 12 times stronger than the oak.

It will be noticed that the beams experimented upon in Tables VIII., IX. and X. are not of the strongest form of section. These defects, however, have long ago been remedied by the introduction of those composed of a web plate, to which double angle-irons, duly proportioned, are riveted, and form the top and bottom flanges of the girder, as shown in section in Table XII. Latterly beams are often rolled solid of the same form as that shown in Table XI.; but as we have fully investigated this subject in 'The Application of Iron to Building Purposes,' and is analytically considered in Chap. XIV. of this work, we may refer the reader desirous of gaining further information on the strength of beams to that volume, and to our concluding chapter on the strength of materials, than to pursue the subject more in detail.

19. From the foregoing experiments, relative to the weakness of jointed timber, and from the great difference which exists between the resisting powers of iron and wood, it is evident that any combination, however well executed, is not calculated to insure the requisite strength for sea-going vessels subject to severe strains. On the contrary, it appears obvious that a vessel constructed with iron frames and covered with wood sheathing is a decidedly weak and unsatisfactory structure. It is true, that a vessel of this kind may be strengthened, as before stated, by stringer plates and diagonal bracing, but to do this is not to adopt the form best calculated to give the required strength; it would be preferable and cheaper to make the ship entirely of iron, and dispense with the wood sheathing altogether. The longitudinal and cross sections, figs. 40 and 41, will clearly explain this mode of construction.

### *Different Methods of constructing Ships of Iron and Wood.*

20. From the foregoing diagram, it will be observed that two wide longitudinal stringers, *a*, *a*, run the whole length of the ship on each side, and between these are a series of diagonal

Digitized by Google

plates or stays, *e*, *e*, *e*, &c., riveted on the exterior surface of the transverse frames in order to unite them in the shape of a side-girder equal in height to about two-thirds the depth of the ship. This plan of fastening the sides is certainly advantageous, and may be considered as an equivalent for those defects which we have noticed in regard to the very limited power of resistance obtainable from the exterior jointless covering of wood. As regards its powers of resistance, in retaining the ship in form, and in preventing her going to pieces in a heavy plunging sea, it must appear evident, that the lower stringer plate should have been much more extended, carried lower down the sides to render it available in stiffening the ship, and in affording that resistance to prevent her becoming hogged or tearing herself to pieces under strain.

In the lower part of the hull, the longitudinal keelson A, and the plates and angle-irons *a'*, *b*, *c*, *d*, will materially assist in strengthening those parts, but they are decidedly imperfect when compared with an iron floor closely riveted, and a carefully connected exterior covering of iron plates.

21. Taking the vessel at 206 feet long, 32 feet beam, and 24 feet deep, it may be shown, by the usual methods of calculation, that the strength of this description of vessel is not one-half the strength of an iron ship of the ordinary construction, and only about one-third that of a well-proportioned and well-constructed iron vessel. These are facts entitled to consideration in this form of structure, as the vessel, of which we have given illustration, would be broken in two with one-half the weight of her displacement, or 1,200 tons, and one-fourth of that weight, or 600 tons, suspended from each end, when supported in the middle, would also produce the same effect.

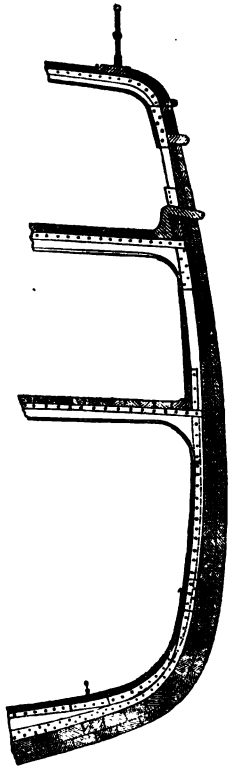
22. It has been proposed, in order to strengthen vessels of this description, to have them double planked, as shown in fig. 42; but this would still be inadequate to meet the requirements of strength in a sea-going ship. This combination cannot, therefore, be recommended, and in every case, where safety is a primary consideration, there is no material so good, and no construction so perfect, as that of a well proportioned and a soundly constructed iron ship.

23. We might enlarge upon this subject if we had the power

Digitized by Google

to recommend it or any other modification of its construction. We are, however, convinced that the two materials are seldom united in the constructive arts with any degree of advantage, especially in cases where great strength is required, and more particularly in constructions which have to contend with forces calculated to tear them asunder. In these respects, the composite principle cannot be considered a good one; nevertheless, before dismissing the subject, it is necessary that we should notice Mr. M'Laine's (of Belfast) principle of uniting iron and wood for purposes connected with the navy.

Fig. 42.



Mr. M'Laine, in advocating this principle, states, 'that the principal strength of an iron vessel is located in the plating, and that the framing is of little value except to keep the plating in shape; that it is, therefore, a mistake to retain only the comparatively useless iron frame in composite vessels; and that it is much simpler, and more in accordance with correct principles, to retain the iron skin to give strength to the composite structure.'

It is also stated, 'that the destruction of iron fastenings, in coppered vessels, is caused by the leakage, holding in solution oxide of copper, chiefly taken up while filtering through the paper or felt underneath the copper sheathing; the leakage passes down the inner surface of outside planking, and if it come in contact with iron, the oxygen of the oxide of copper having a greater affinity for iron than copper, the atoms of copper are deposited, and oxide of iron is formed; it follows therefore, that any iron framing or plating coming in contact with the outside planking must be subject to serious deterioration where there is leakage, and that it would be highly desirable to prevent the leakage coming in contact with the iron of the structure.'



Digitized by Google

In order to accomplish the aforesaid desirable results, Mr. M'Laine proposes to construct vessels having keel, stem, stern-post, frame, and outer planking nearly the same as in an ordinary wooden vessel; but, instead of constructing the ceiling or inner planking of wood, he would construct it of iron, united all round at bottom and ends of vessel, and made thoroughly water-tight, forming a complete inner skin with beams, stringers, keelsons, bulkheads, platforms, &c., of iron, as shown in figs. 43 and 44, 45 and 46. The greater part of the wooden frame to be merely of dimensions sufficient for bolting wooden planking to, and inserted between (and fastened with fore-and-aft screw bolts to) angle-iron frames, riveted all round outside of the iron ceiling. He further states 'that the wooden floorings should be made deep in the throat, and stiffened with plates on each side, riveted to angle-iron frames, or iron floors to be fitted inside of iron ceiling to give requisite transverse strength. Apron, inner-post, and deadwood to be inserted between, and bolted to large angle-irons, riveted on iron ceiling, with extra bolts through ceiling, if requisite. Outer planking, within the influence of copper sheathing, to be fastened to wooden frames, with screw treenails or yellow metal bolts. Top timbers of frames to be, by preference, composed of teak. In wake of armour plates, spaces between frames to be filled in solid with teak, iron ceiling increased in thickness, and perpendicular angle-iron web stringers introduced at intervals, to resist shot, and strengthen the vessel.'

'Owing to the iron ceiling being perfectly tight, no foreign matters could get into the spaces between the frames, to decompose in the bilge water and generate gases injurious to animal life and productive of decay in timber exposed to their influence; these spaces would, therefore, be eminently eligible for the introduction of a thorough system of ventilation through the vessel, by driving a current of fresh air, taken from above, through box-keelson, thence through apertures in bottom of keelson opening into each space between floors, then up through the spaces between frames, and out into 'tween-decks through apertures in iron ceiling, grated over and fitted with adjustable covers to regulate amount of ventilation. A three-horse engine would probably supply power sufficient for the ventilation of a

Digitized by Google

ship of 3,000 tons, would be of great service, especially at night, in providing crew with pure air, and the ventilation would immensely increase the durability of the vessel.'

'Vessels constructed as described would combine all the good qualities of both iron and wooden vessels, and would, in some respects, be much superior to either. They would have the plating, frame, beams, stringers, keelsons, bulkheads, platforms, &c., of an iron vessel, capable of being made of any required strength, and the wooden planking, bolted to firmly fastened timbers, would form a cellular construction adding strength quite equal to that of a similar weight of iron. It would not be necessary to increase the scantling of wooden frame and planking in proportion to tonnage, and a vessel of 4,000 tons would be about the same weight as an iron vessel of same strength and size. The weight of vessels of the smaller class would range about a medium between that of iron and wooden vessels. Fig. 46 shows an arrangement for decreasing materially the weight of iron and wooden framing, without much reduction of strength; as teak, weight for weight, is treble the strength of iron, and a plank bent in one length perpendicularly between frames, and well fastened with screw bolts to outer planking, would be an economical application of material, and give a good result.

'The after-end of these vessels could be made of any strength required to withstand the vibration of screw shaft by means of bulkheads, stringers, platforms, &c.

'They would be incomparably safer, if stranded, than any vessels ever before built, in consequence of having wooden keel, planking, and floorings, to withstand the first shock of getting on shore, and the subsequent chafing, thus possessing all that contributes to the safety of a wooden ship, and having in addition a water-tight iron skin, with bulkheads, platforms, &c., and iron frames fitted *outside*, which, together with wooden frame, would have a tendency to push up iron ceiling, and prevent its being perforated. The iron portions of the structure of these vessels would last for an indefinite period, as they could be thoroughly prevented from oxidation by paint, cement, or bituminous coating, and would be entirely free from the injurious influence of the copper sheathing, as the leakage would pass down the inner surface of outside planking to water



Digitized by Google

Fig. 43.

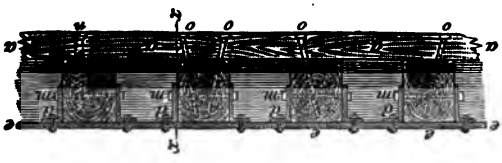


Fig. 44

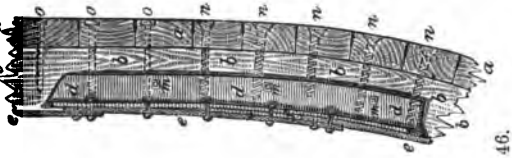


Fig. 46.

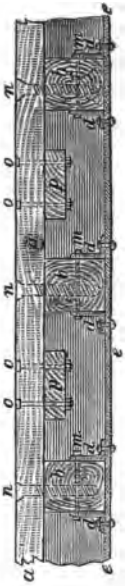
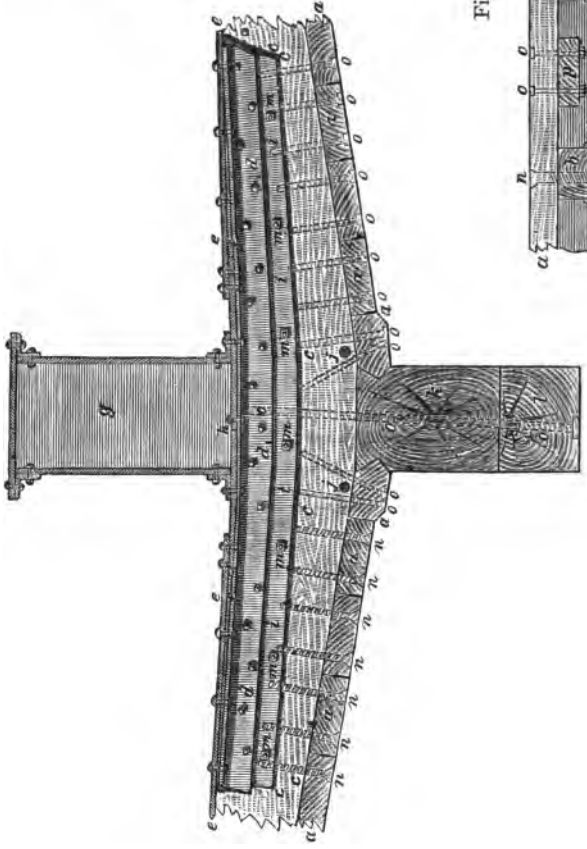


Fig. 45.



Digitized by Google

spaces between the floors, without coming in contact with iron, and be pumped out by centre or bilge pumps; while the wooden portions of structure (if upper works were composed of teak) would, under the influence of currents of pure air and the absence of deleterious gases, probably last for a hundred years.

'The system of construction described is specially applicable to vessels of war, as it enables any required amount of strength to be given to the structure, and the iron ceiling, with frames outside, is eminently suitable for assisting in the formation of a shot-resisting broadside.'

Figs. 43, 44, 45, and 46, show the sections of a composite vessel of about 2,500 tons register.

Fig. 43. Horizontal section of broadside.

Fig. 44. Perpendicular section of do., at *x*.

Fig. 45. Transverse section of keel, keelson, &c.

Fig. 46. Horizontal section of a broadside, showing mode of increasing frame spacing, when considered desirable.

*a, a, a, a*, figs. 43, 44, 45 and 46. Outer wooden planking, 4 inches thick, fastened to wooden frame, with screw treenails, or brass bolts, 12 inches long.

*b, b, b*, figs. 43, 44, and 46. Frame timbers, sided 8 inches and moulded 9 inches, inserted between, and bolted to angle-iron frames with galvanised iron screw bolts about 16 inches apart.

*c*, fig. 45. Wooden flooring sided 11 inches at throat, 8 inches at ends, moulded 18 inches at throat, 12 inches at ends, and inserted between angle-iron frames.

*d, d, d, d*, figs. 43, 44, 45, 46. Angle-iron frames, 5 inches × 3 inches × $\frac{1}{2}$ inch, riveted all round to outside of iron ceiling.

*e, e, e, e*, figs. 43, 44, 45 and 46. Iron ceiling, $\frac{7}{8}$-inch thick, united all round at bottom and ends of vessel, and made thoroughly water-tight, forming a complete inner skin of iron.

*f, f*, figs. 44 and 45. Liners, filling clinker spaces of ceiling, in wake of iron frames.

*g*, fig. 45. Box keelson, 18 inches × 33 inches.

*h*, fig. 45. Ventilation aperture through bottom of box keelson into space between floorings.

*i*, fig. 45. Stiffening plate, to be fitted on each side of wooden floors, and riveted to angle-iron frames to give transverse strength. If space between frames were increased, floors could be sided larger at throat, and stiffening plates would not be requisite; or iron floorings could be introduced instead of iron ceiling.

*j, j*, fig. 45. Limber holes.

*k*, fig. 45. Main keel.

*l*, fig. 45. False keel.

*m, m, m, m*, figs. 43, 44, 45 and 46. Fore-and-aft galvanised iron screw bolts.

*n, n, n, n*, figs. 43, 44, 45 and 46. Screw treenails.

*o, o, o, o*, figs. 43, 44, 45 and 46. Brass bolts.

*p, p*, fig. 46. Perpendicular planks, 10 inches × 3$\frac{1}{2}$ inches, bent in one length from keel upwards, between frames, and fastened to outer planking with brass screw bolts.

Digitized by Google

The iron portion of the structure, according to Mr. M'Laine, 'would be first finished complete and lightened, perhaps leaving each alternate iron frame loose, to facilitate the fitting of a wooden frame. All the iron surface in frame spaces to be carefully cemented before working on the outer planking, though there would be little tendency to oxidation, owing to the ventilation currents through frame spaces, and not much risk of excessive leakage, as the vessel could be made so strong, that if once tight it would be likely to remain so.'

24. We have given increased space to Mr. M'Laine's principle of construction, in his own words, because it probably gives the best combination of wood and iron as applied to the construction of ships. We, however, consider it inferior to, and more expensive than, the iron vessel with double bottom; and as this may ultimately prove correct, we give a further detailed description of the latter system of construction at Chap. XI.

In this investigation, we have not denied that vessels sheathed with timber and copper-fastened are superior to those of iron as regards fouling and the adhesion of molluscs and marine vegetation to their bottoms. These are difficulties which every new system of construction has to contend with; but it does not follow that some effectual remedy may not be in reserve for correcting this evil. The necessity of the case may, in all probability, bring the remedy; and we have yet to discover some chemical or electrical process by which we are to discharge or, what is decidedly preferable, prevent the adhesion of animal and vegetable life to the bottoms of iron-plated vessels. Under the impression that means will be obtained for remedying this inconvenience, we can see no reason for abandoning the iron construction. On the contrary, we have neither hesitation nor misgiving in adhering to the superior merits of iron, and, even supposing that no further progress is made for the prevention of fouling, iron for the construction of ships will, according to our opinion, still retain its ascendency over every other description of material in the formation of vessels of war. Besides, there is every prospect that the improvements in the manufacture of steel will tend still further to increase the strength, lightness, and superiority of these important structures.

Digitized by Google

# CHAPTER VII.

## ON THE VARIED FORMS OF CONSTRUCTION OF SHIPS OF WAR AND THEIR ARMAMENT.

1. At the commencement of the Crimean war, ten years ago, His Imperial Majesty the Emperor of the French first suggested, that to cover the sides of ships with thick iron plates would render them impervious to shot, and the first ship that, properly speaking, had her sides protected in this way was the 'La Gloire.' She was cased with 4½ inches thick armour plates, fastened with long bolts screwed into the timbers, and was considered at the time to be impregnable and perfectly shot-proof; which was the case, as the heaviest ordnance then in use was the 68-pounder smooth-bore gun.

The success of the 'La Gloire,' and the apparent security which she indicated in her new dress, led to distrust in every other vessel that was not protected by a covering of impenetrable armour plate. For a time it was doubtful to what extent this new system of armour covering was serviceable, and how it could best be applied to existing ships. This was a debatable point, and many were the projects elicited for that purpose, and the rooms of the Admiralty were inundated with contrivances, from which it was impossible to make a selection calculated to meet the requirements necessary to convert two and three-deckers into serviceable armour-plated ships. The result of all this conflicting testimony was that new ships must be built; and to render them as nearly as possible fire-proof and shot-proof, it was decided to build them entirely of iron. In the meantime it was necessary to be prepared, and not only were the 'Warrior' and 'Black Prince' placed upon the stocks, but several of the large two and three-deckers were cut down and lengthened and plated

Digitized by Google

in order to meet the exigencies of the time, in case the country should unexpectedly be engaged in war.

2. No sooner were these matters settled and provision made for the worst, than it was found that great improvements were likely to be made in guns, both as regards range and power. This discovery called into action the two rival constructors, Whitworth and Armstrong, and after a long series of experimental tests, it was ascertained that the old ordnance was exceedingly defective; that every gun, great or small, should be rifled, in order to give long range and precision to the projectile; and that to give the required strength to the guns, they would have to be made of wrought iron or steel. It was also asserted that the old-fashioned method of putting the ball and charge in at the muzzle was a bad one, and hence followed the breech-loaders, and that complexity of construction which made the cure in some cases worse than the disease. Ultimately it was decided that breech-loading was neither safe nor convenient, and for heavy guns it was decided to retrace the steps previously taken, and come back to the old plan of introducing the charge through the muzzle.

3. For many months the new rifled constructions were confined to guns of small bore, 12 to 40-pounders, all of them breech-loaders. Then followed those of larger calibre, from 70 to 110-pounders, which were also constructed as breech-loaders, and these held their ground for a time, until it was found that the 110-pounders produced less damage on the sides of an iron-plated ship than the old 68-pounder. During this state of change and vacillation about guns and iron-plated ships, a committee was appointed, called the Iron Plate Committee, conjointly with the War Office and the Admiralty, to determine experimentally the composition, properties, law of resistance, &c., of iron plates and shot, as will be seen on reference to the following instructions submitted to the committee:—

'War Office: *January* 12, 1861.

'The experiments should be directed to ascertain the thickness, size, and weight of iron plates of a specific composition and manufacture that will resist shot of given shape, weight, and material, at given velocities, striking both directly and at given angles.

'The resisting powers of different qualities of iron plates

Digitized by Google

must be tested; hence the history of each plate should be ascertained, following it up from the first stage of manufacture until it became a wrought-iron plate.

'The chemical composition of the iron at each process of manufacture should be ascertained; the specific gravity and lay of the fibre of the plates experimented upon should be noted, as well as the composition, density, and mode of manufacture of the shot; but it will be impossible to decide on the greater or less resistance of the plates unless the velocities of the shot be measured, either by Professor Wheatstone's or one of the foreign instruments. Any variation in the velocity of the shot should be carefully recorded, together with every particular of each experiment. If this be not done, no accurate conclusions can be drawn from them.

'The committee should begin the experiments on a small scale, for if all the facts above mentioned be carefully ascertained and traced up through certain gradations of models at the known high velocities required, they would, at a very reduced cost in money and time, afford data for devising a few final experiments on a larger scale; because all the particulars of the plates in the small experiments being known, allowance could be made for the difference in the composition of iron plates on the larger scale, which necessarily arises from the imperfection of means of manufacture; and the law being the same whether for large or small plates, that being once ascertained, the committee would know what practical experiments to make on a large scale.

'All the records of all previous experiments that have been made should be given to the committee, to be examined and classified. The committee should also be called upon to submit a scheme of experiments.

'The experiments should be carried on at Woolwich, Shoeburyness, or Portsmouth, or, if preferred, in the neighbourhood of some iron works, as might be best for the convenience of the gentlemen engaged.

'The Government would, by means of these experiments, be in a position to specify the proper mode of manufacture for these plates.

(Signed) 'B. HAWES.'

Digitized by Google

From the above it will be seen that the committee had important duties to perform, and although not limited in their researches, they were especially required to investigate every circumstance connected with iron, as applied to ships and forts, and they were also expected to recommend and conduct experiments on a large scale, in order, not only to correct defects in the manufacture and improve the quality of the iron, but to determine its properties and its powers of resistance to projectiles at high velocities. These duties were energetically and carefully performed on the part of the committee, and after four years' labour they were relieved from further duty, in the month of August 1864.

4. During the time of the committee's existence, not less than twenty iron-plated targets were made and experimented upon, exclusive of other experimental researches at Manchester and Portsmouth, to determine the effects of impact and the resistances afforded by different qualities of manufactured plates, of various thicknesses and of different forms and conditions, as applied to ships of war. In addition to those duties, the committee undertook the inquiry as to the best and most secure mode of attaching armour plates to the sides of ships, whether constructed of iron or of wood, and a number of interesting experiments were instituted and conducted for that purpose. At the commencement of the labours of the committee, the only vessel, upon a large scale, intended for the reception of armour plating was the 'Warrior,' of 6,039 tons burthen. This vessel was exclusively prepared for a covering of plates, 4½ inches thick, to a depth of 6 feet under the water-line, and supported by a backing of teak and oak, varying from 18 to 20 inches thick, between the armour plates and the iron skin of the ship. The armour plates were fastened through the wood-backing and the skin of the ship, by bolts 1¼ inches diameter, counter-sunk into the armour plates and screwed inside between the frames of the ship. This arrangement was considered, in the absence of experiment, the most perfect that could be adopted at the time; but subsequent investigation showed that the bolt fastenings were much too weak, and that in place of a double line of backing, a single thickness of teak or oak would prove, with an additional thickness of armour

Digitized by Google

plate equivalent to the weight of the abstracted timber, sufficient in its powers of resistance to prevent the entrance of the shot and shell at that time in use. Acting upon this principle, the backing to the armour plates of the most recent construction is from 9 to 10 inches thick, and the bolts are enlarged from 1½ to 2¼ inches diameter, making the strength of the retaining bolts three times that of those in the 'Warrior.'

5. At the commencement of the experiments by the committee, it was considered desirable to ascertain whether the wood backing could or could not be entirely dispensed with without any increase of weight, and to give the difference to an increased thickness of the armour plates. This consideration was of great importance, as it was found that Mr. Whitworth had fired a hardened steel shell through a 4½ inch plate, and lodged its explosive contents in the backing and sides of the ship.

This experiment caused considerable alarm in the minds of nautical men, as to the safety of the ship from fire, and particularlarly those built of wood, if penetrated with shells. To obviate these risks, several targets were made for the purpose of dispensing entirely with the wood backing, and to determine the effects of vibration or jar produced upon the plates and fastenings, by the impact of both shot and shell. *These were not competing targets*, although treated as such by the press, but were made for the exclusive purpose of ascertaining the actual state of a vessel built entirely of iron and armour-plated, without the intervention of timber backing. The experiments were conclusive and instructive, as the results clearly showed that a cushion of some compressive substance was requisite to receive the effects of the blow, to deaden the vibration, and secure the fastenings from fracture.

6. Other experiments of an interesting and instructive character were conducted by the committee, some of them to determine the law of oblique firing at different angles, varying from 15° to 45°. These experiments were made on different thicknesses of plates, in order to determine the penetrative powers of variously formed shot, when fired at angles to the surface of the plate. Experiments were also conducted to determine the law of resistance of plates of different thicknesses to projectiles, fired *point blank*, at short distances, and at right angles to the plate.

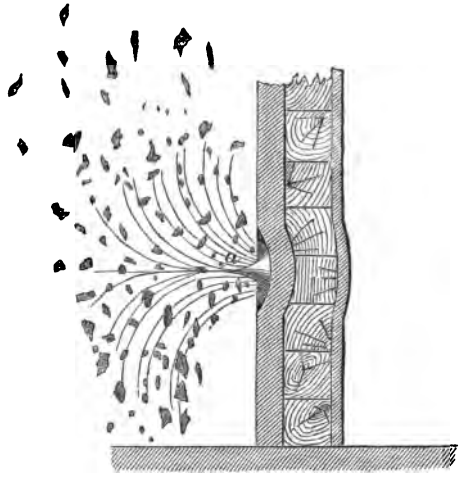
Digitized by Google

These were done with great care; and in order to determine the law of perforation, a long series of experiments was conducted on statical pressure, showing the power required to force a steel cylinder through plates of different thicknesses; and these were carefully compared with those on impact, and deductions made therefrom. These experiments will be found instructive as well as useful, and may be referred to in the Reports of the Iron Plate Committee.

7. During the progress of the first series of experiments conducted by the committee, only cast and wrought-iron shot were employed against the targets. A few small round and flat-ended steel ones of about 1½ lbs. weight were fired from a light gun, called the wall-piece; but the shot from the large guns were either cast or wrought iron, some spherical, such as the 68-pounder, and others, such as those from the rifled guns, were cylindrical bolts, varying from 12 to 350 lbs. weight.

In the earlier stages of the experiments it was found that as much depended upon the metal of which the shot was composed as upon the resistance of the armour plates. It was very soon discovered that neither cast nor wrought iron was the material for penetration, as nearly one-half the force was lost in breaking up the shot if made of cast iron, and the same result was observed in the distortion and flattening of wrought iron by compression when it struck the surface of the plate. These facts were exceedingly interesting, the cast-iron shot invariably breaking up at the point of contact, leaving at times a sharp pointed cone, as at *a*, fig. 47, indented and sticking fast in the plate. For some time the committee were not aware of the dangerous effects of these splinters or frag-

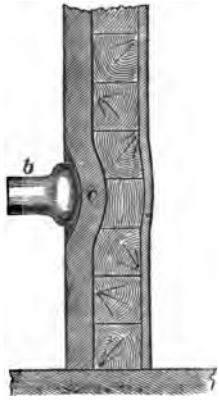
Fig. 47.



Digitized by Google

ments, being scattered to great distances and to elevations which required from 30 to 40 seconds before they made their appearance in a perfect shower of iron; some of the pieces weighing from 5 to 10 lbs. The effect of a wrought-iron shot was the reverse of this: it made about the same amount of indentation, but with this result, that its form was changed into the shape of a railway buffer, with its greatly enlarged compressed surface converted into the form shown at *b*, fig. 48. From this description of shot there was no danger from splinters unless the force was sufficiently powerful to pierce the plate, in which case the part, at *c*, was carried right forward through the backing, with large pieces of iron and splinters, carrying destruction and devastation in their passage through the ship. These results will, however, be more fully appreciated when we come to consider the subject more in detail, and to which it was nevertheless necessary to direct attention at the time, in order to obviate the danger by which it is surrounded.

Fig. 48.




8. Having accounted for a few of the changes that have been in progress for the last four years, and the causes from which they proceeded, it now becomes evident that the art of constructing both plate and shot requires careful consideration, in order to effect an improvement, and to establish the principle of a sound and more perfect system of operations in the construction of ships of war. Before entering upon this very important question, it will, however, be necessary to draw from the experiments such conclusions as appear to indicate the proper weight and size of guns and the weight of armour plate a ship is calculated to carry.

As respects the former, there cannot exist a doubt as to the necessity of having guns of the largest calibre. Sir W. Armstrong has already settled this question; and if a gun, weighing 22 tons, capable of discharging a shot of 600 lbs. weight at a velocity of 1,200 to 1,400 feet per second, can be made (and there is every reason to believe that ordnance of still larger dimensions can be manufactured, provided the necessary caution

Digitized by Google

is observed in the construction), it then becomes no longer doubtful what would be the effect of ordnance of this weight on iron-plated ships. It has been proved that 350-pounders will go right through 6-inch armour plates at a range of 200 yards, and we naturally infer from this that the same results would follow from 600-pounders at five or six times the distance. The question which presents itself for solution is, therefore, what description of armour plates or defence can there be attached to an iron ship to keep out such unwelcome visitors? It has been stated that vessels are unable to support such heavy guns, but that is probably a mistake, as they only require to be prepared for the purpose. At the same time it must be observed that it is only vessels of large dimensions that are calculated to carry a sufficient thickness of plates to resist ordnance of this immense calibre. Vessels of great magnitude, loaded with such a coat of mail, would to some extent be helpless hulks on the water, and, according to our judgment, would not be so manageable nor yet so active in the presence of an enemy as vessels of one-half the size. Viewing the subject in this light, we have to submit for consideration what have already been communicated to the Admiralty, namely, the views entertained as to the magnitude, form, and other conditions which present themselves in the designs and construction of ships of war. It is not our intention to offer any opinion as to the lines, stability, and other properties, which chiefly belong to the Controller of the Navy, Mr. Reed, and other competent authorities. We may, however, shortly refer to the opinions entertained on this subject by Mr. Reed, Captain Coles, Messrs. J. Scott Russell, Laird, Grantham, Napier, and those who have directed their attention to the construction of vessels for purposes of both war and commerce. To these opinions we respectfully submit, and yield unhesitatingly on the above points to their superior judgment.

9. On the question as to the class of vessels best adapted for a new and almost untried service, there is yet much to learn, and so long as the public mind remains unsettled, or till some fixed principle is established, every person at all conversant with the subject considers himself entitled to give an opinion. We happen to be in this condition at the present moment, and in this

Digitized by Google

state of vacillation we can only suggest what appears to us—taking into account the prospect of future improvement in the construction of both ships and guns—best calculated to meet the difficulties by which we are surrounded. With these remarks, and to render our views more intelligible, we have to notice—

1st. Those of Mr. Reed, the present constructor of the navy.

2nd. Those of Mr. Scott Russell, Grantham, &c.

3rd. The turret system of Captain Coles.

4th. Those of Mr. M'Laine, and

Lastly. Those of the author.

10. The plan, communicated to Her Majesty's Government, of concentrating a battery of heavy guns at midships, and armour-plating the ship at the water-line from stem to stern, was favourably received by the Admiralty, and ultimately led to Mr. Reed's appointment as Naval Constructor. Mr. Reed received a practical education, at Portsmouth, as a shipbuilder, and having been Secretary to the Institution of Naval Architects from its foundation to his appointment of Chief Constructor, he was the better prepared for the task he had to perform, in the transfer now in progress from wood to iron. United to this, and his consistent advocacy of iron as the only material suited for armour-plated ships,* we arrive at the conclusion that the selection was appropriate, and not without advantage to the public service.

Mr. Reed's system of construction consists in what we have just described; a concentrated battery in the centre of the ship, a belt of armour at the water-line, and, where practicable, preparations for the support of four large guns, two at the bow and two at the stern, independent of the principal battery at midships on the fighting deck. These guns are protected by strong armour plates, as in the case of the 'Lord Warden' and 'Lord Clyde' class, and, moreover, 5½-inch thick plates are introduced over the guns, and, instead of being carried along only one portion of the sides, they cover the whole vulnerable parts of these vessels from stem to stern. In addition to the 4½-inch armour plates, an extra thickness of 1½-inch plate is placed at the water-line between the backing and the sides of

* We understand that the first design submitted to the Admiralty by Mr. Reed was for a corvette, to be built wholly of iron.

Digitized by Google

the ship, giving 6 inches of iron to be pierced before either shot or shell can enter the ship.

According to a statement in the *Times*, it is said 'that the most singular feature in the "Lord Warden" is the high heavy bow, which towers above her fighting deck, which is intended to be armed with thick plates, to give protection to the battery of heavy guns placed in that part of the ship. Hitherto it has been the practice in war ships, and especially in those forming the iron-clad squadron, to give great roundness or bluffness to the bow above the water, for the purpose of affording space for guns firing right ahead, and to make the ship very narrow below the water immediately beneath this bluff and heavy bow, in order to give speed, to which everything else would appear to have been sacrificed. The consequence of this has notoriously been a great disposition to plunge in our ships of war, and especially in those iron-plated frigates in which the full bow above, unlike the stem of the "Warrior," is burdened with armour. In the "Lord Warden" all this will be corrected by the long under-water bow, projecting some ten or twelve feet beyond the stem. It will give such buoyancy to that portion of the vessel, that, although an enormous thickness of armour is carried all round the bow aloft, and four large guns firing ahead, in a line with the keel, are protected, it is expected that the entire fore part of the ship will be more satisfactorily water-borne than the bows even of the frigates which carry no armour at all. With this improvement is also associated another equally important, namely, a total change in the form of the vertical sections of the bow; the new form of section being U-shaped, in opposition to the old V-shaped bows, to which the Admiralty have until now so pertinaciously clung. The slightest thought will convince any one that when the bow of a ship is formed like a V it will cleave the water with facility as the ship plunges, and thus tend to increase the violence of each plunge. A bow, on the other hand, formed like a U will be obviously greatly obstructed by the water in its descent, and thus the violence of the plunge will be diminished. For these reasons it is anticipated that, in spite of the great weight of armour, 1,300 tons, which the "Lord Warden" will carry, which exceeds that of any other vessel afloat, she will be

Digitized by Google

easier in a seaway than any previously constructed iron-cased frigate. This form of construction will, at the same time, give greater space and airiness in each deck, and additional security for the powder and shell magazines, which will be kept at least 8 feet below the water, and within the shelter of the armour-casing.'

The above extract illustrates one of the most marked features of Mr. Reed's vessels in so far as their 'lines' are concerned, viz., the employment of a very long floor in proportion to the length of the ship, which obviously is well adapted to combine with what is now known professionally as the 'ram bow,' in which the stem of the ship projects below the water greatly in advance of the upper portion of the hull. And before discussing other features of the system it may be well to explain that this is quite a novel feature in the construction of our men-of-war, and not, as some have supposed, a mere adjunct or consequence either of a particular form of stem or of a particular form of midship section. That it is not necessarily associated with an upright stem may be seen from an inspection of the drawings of almost any fast mail-steamer built for ocean purposes, and that even the ram bow may be dissociated from the full forward sections that constitute the 'long floor' will be apparent to any one who has inspected the large and powerful Italian turret-vessel 'Affondatone,' building on the Thames by the Millwall Company. As far as regards the extent to which the form of the midship section affects the U-form of bow, it is to be observed that the employment of a very full section, or flat floor, in a short ship necessarily causes an approximation to this form forward; but, on the other hand, there are many hundreds of ships built with flat floors in which this form of bow is in no degree approached. This latter is almost universally the case in ships built for high speed; while in the shorter ships, in which a great speed is not attempted, but in which a great cargo-carrying power is sought in conjunction with a light draught of water, it often is approached, but these cases could not possibly have served Mr. Reed for models in aiming at the high speed sought in the 'Bellerophon,' 'Pallas,' and other ships of his design. It is at least certain that the buoyant bow was not introduced into Her Majesty's navy until these vessels were laid down.



Digitized by Google

Before passing from this feature it is important that we should remark that it is not necessarily allied, as seems probable at first sight, with great bluffness or fullness in the bow lines. The lower water-lines of such a ship as the 'Bellerophon' are undoubtedly less fine than those of the 'Warrior;' and the bow of the wooden sloop 'Amazon,' which is also of the type of form in question, is certainly less fine near the keel than that of the 'Alabama.' But, on the other hand, it is quite practicable to fine the upper water-lines by means of the buoyancy gained with the full lines below, and thus to secure, on the whole, as small an average 'angle of entrance' with the new form of bow as with the old. This is not, however, strictly the case in the ships of war just mentioned, the designer of which considers, apparently, that the entrances or bow water-lines of previous vessels were unnecessarily sharp.

A second feature observable in the *form* of Mr. Reed's vessels is a marked difference in their draught of water forward and aft. Most of the ships of the navy have previously been designed with an equal immersion at both ends, or on what is called 'an even keel.' Even in light-draught vessels, however, Mr. Reed immerses the stern to a definite extent more than the bow; while in ships in which high speed is of much greater consideration than a shallow draught, he carries the difference to what many must consider an extreme. In the 'Bellerophon' the draught of water will be five feet, and in the 'Pallas' six feet, greater aft than at the bow—a state of things unexampled in war-ship building. It cannot be denied, however, that the objects thus aimed at are highly desirable; the first being the deep immersion of the large screw propellers, which are driven by powerful engines; and the second, the power of turning the ship quickly on her 'heel' under the action of the rudder. It is no part of our present purpose to say to what extent these objects will be accomplished by the means employed; but the interest which attaches itself to such novel and important experiments in the propulsion and manœuvring of these large armour-clad ships of war is necessarily very great.

We must look upon this novel form of construction as strictly experimental. Should it be found, after trial, to affect the steaming powers of the ship, there is still in reserve the power

Digitized by Google

to lighten the load of the vessel at the stern, and to bring her down at the bow, giving her a more even keel, so as to secure the most favourable line of flotation.

Another important feature in Mr. Reed's system is the adoption of deep longitudinal keelsons, and the cellular system of construction in the hull of the ship, as also the increased number and strength of the stringer plates on the upper deck, whereby the sectional areas are in closer correspondence with that of the hull, and from which is derived greatly increased strength in the bearing powers of the ship. In the adoption of this principle of construction—long recommended by the author—Mr. Reed has exercised a sound discretion, as he saves considerably in weight by dispensing with more than one-half the number of transverse frames, and gives, with the double bottom, greatly increased security, in case of accident to the outer plating. The 'Bellerophon' is built on this principle, of which we give a drawing and description,* including the calculations, showing the great superiority of this vessel when compared with other constructions either in the war or the mercantile navy.

In speaking of the general features of construction, Mr. Reed states 'that we should employ iron armour of some kind, and to some extent, in every class of fighting ship that will carry it, large and small; that we should employ a few large guns, wherever practicable, in preference to many small ones, and give these large guns as great a range of fire as possible; that every class of ship should be protected with armour throughout her entire length in the region of the water-line; that the rudder head and steering apparatus should be protected; that every vessel intended for sea-going purposes should stand up well out of the water, be well lighted and ventilated, and carry efficient masts and sails—in fact, be as unlike the ill-fated "Monitor" in all these respects as possible; that every such vessel should be made strong enough to stand the shock of being used, upon an emergency, as a ram against vessels of her own class; that small war vessels, if armour plated, may be built of wood, but that when a very high speed or very large dimensions are required we should build in iron; that when built of wood the hull should be made solid throughout, in the wake of the

* *See* Chapter XI.



Digitized by Google

armour; and, finally, that every sea-going ship of war should be so formed, and have her weights so distributed, that she will be well supported as far as may be at every part, and have no heavy overhanging parts, to cause her to strain and work when knocked about in a sea-way.'

Mr. Reed states 'that ships of war should be made strong enough to answer, if necessary, as rams, not against ships very much larger and stouter than themselves, but against vessels of their own class.'

From this it would appear that most of our war steamers should be built on the ram fashion, to be used occasionally when circumstances afford an opportunity of running down an enemy's ship. We are, however, of opinion that it would be more useful to the service to confine the ram class to the larger description of frigates, and, above all, to those fitted with double screws, in order that they may have the power of turning quickly upon their antagonist, and with full speed to inflict a blow that no vessel could withstand.

11. It would be superfluous for us to advocate the views of different constructors with respect to individual opinions, either as regards the material or the forms on which vessels should be constructed. We cannot, however, omit to notice the views of some of those constructors who have done so much as consistent advocates of iron, and its application to new forms and conditions, as exhibited in the labours and writings of Mr. Scott Russell, Mr. Laird, Mr. Grantham, Mr. Napier, and others, who have acted as pioneers and constructors in the changes and improvements which have marked the progress of naval architecture for the last twenty years.

12. Mr. Scott Russell, in his 'Fleet of the Future,' and his able advocacy of a class of vessels calculated to attain high velocities, has conferred great benefits on ship builders, by giving the proper form and construction of ships, whether intended for war or commerce; and Mr. Grantham, by his increased attention to the case of fouling, has also rendered essential service to the conditions of an unsolved problem, namely, how to prevent the fouling and oxidation of the hull of iron-built vessels?

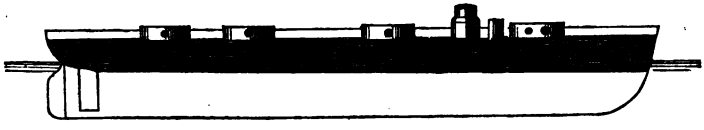
13. The turret system, first introduced by Capt. Coles, has never had a trial at sea, and we have no satisfactory tests, no con-

Digitized by Google

clusive results on which we can depend for the guidance of the Admiralty on this important question. The first idea was a turntable or a number of turntables, 20 to 25 feet in diameter, fixed level with the deck, and on each of these tables was raised a conical or a vertical building or framework of teak varying from 20 inches to 2 feet thick, and to this as a backing the armour plating was attached: the circumference being pierced through with port-holes for one or two guns, according to the size and burthen of the ship. From this it will be seen that the table being supported on a strong centre pivot, with rollers at the circumference moving on the metallic surfaces of the platform and the lower surface of the movable floor, that this portion of the table would revolve by toothed pinions and segments, carrying the guns and platform round to the required point in the line of fire.

Fig. 49 is a representation of the 'Royal Sovereign,' covered with 5½-inch armour plates and containing four vertical revolving turrets, as taken from Capt. Coles's sketches in the 'Transactions of the Institution of Naval Architects for 1863.' Her armament consists of five 300-pounders throwing a broadside of 1,500 lbs.

Fig. 49.



Capt. Coles maintains that his system of revolving shield ships carries a far heavier broadside in proportion to their tonnage than any other description of vessel, and he compares them with the 'Defence,' 'Prince Albert,' and other vessels, to show that the turntable or turret vessels in firing a broadside can bring the whole of their guns to bear in one direction, whilst those of fixed batteries can only fight every other gun. In illustration of this statement Capt. Coles compares an imaginary vessel, which he calls the 'Naughty Child,' with another, the 'Favourite,' on Mr. Reed's plan, showing the line and angle of fire in his case, as compared with that of Mr. Reed in his midship battery, as exhibited in figs. 50, 51, 52, and 53. Capt. Coles observes 'that by way of making a more complete comparison of his system and the broadside system, he will take a vessel of exactly the same tonnage,

Digitized by Google

form, and construction as the "Favourite," and by way of distinguishing the two ships, he will call his ship the "Naughty Child." The only difference between the "Favourite" and the

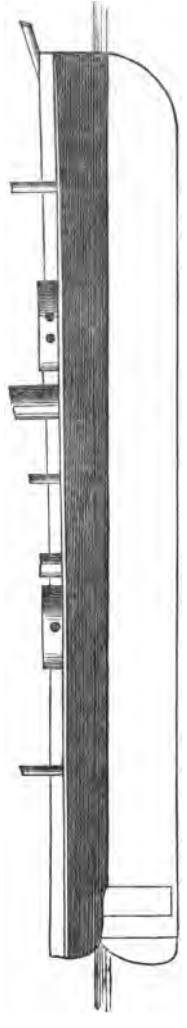


Fig. 50.
Elevation of 'Naughty Child.'

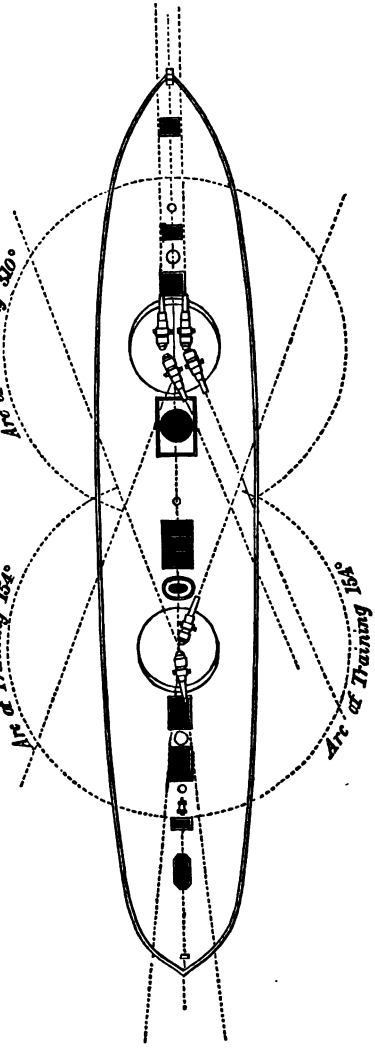



Fig. 51.
Plan of 'Naughty Child.'

"Naughty Child" is, that the latter vessel is fitted with two revolving shields in lieu of one square box in the centre as shown in the above figures.' Mr. Reed having already chosen his armament for the 'Favourite,' viz. :—four 110-pounders

Digitized by Google

throwing a broadside of 440 pounds, he observes he finds that this square box and armament weighs 285 tons, which when worked up into shields would give the 'Naughty Child' two

Fig. 52.
Elevation of 'Favourite.'

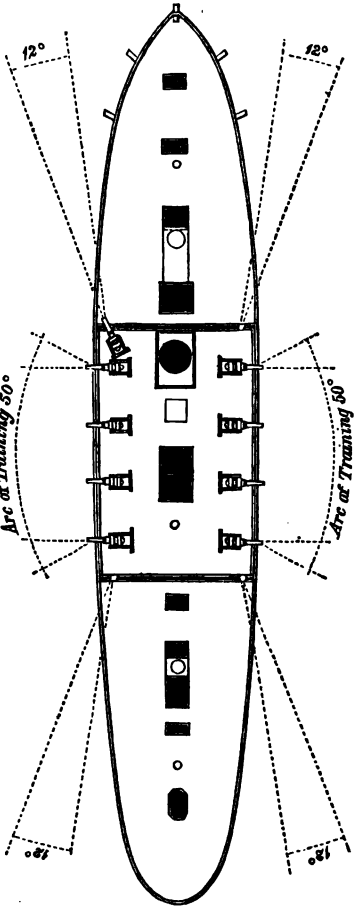



Fig. 53.
Plan of 'Favourite.'

shields, carrying three 300-pounders, equal to a broadside of 900 lbs. Thus, with the same weights, the decks being the same height out of water, viz., 7 feet 8 inches, he states he throws

Digitized by Google

double the weight of broadside. 'May I ask then,' he further remarks, 'why should these two vessels not be equally good sea-going vessels, and have equally good ventilation, for they have the same amount of openings on the upper deck? The "Naughty Child" would have her shields, which, when she was battened down in a gale of wind, would act as hatchways with 5 feet combings to keep the sea out. It will be seen that the deck of the "Naughty Child" is 7 feet 8 inches out of water, and the gun 10 feet. Moreover, the position and elevation of the port hole, in the

Fig. 54.

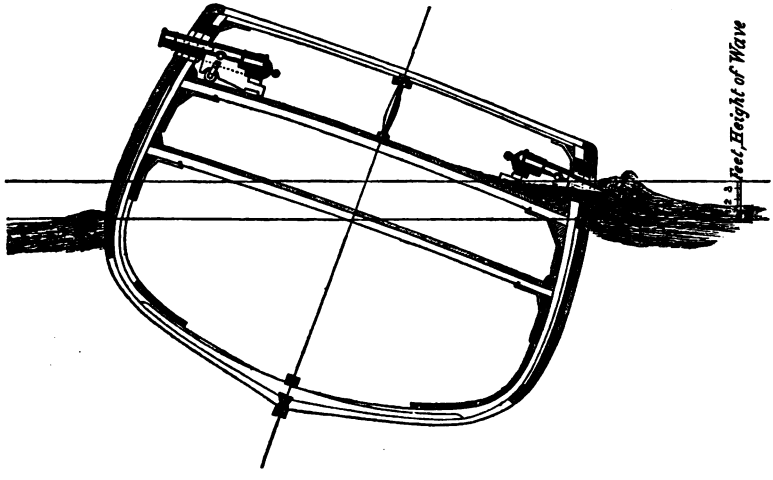
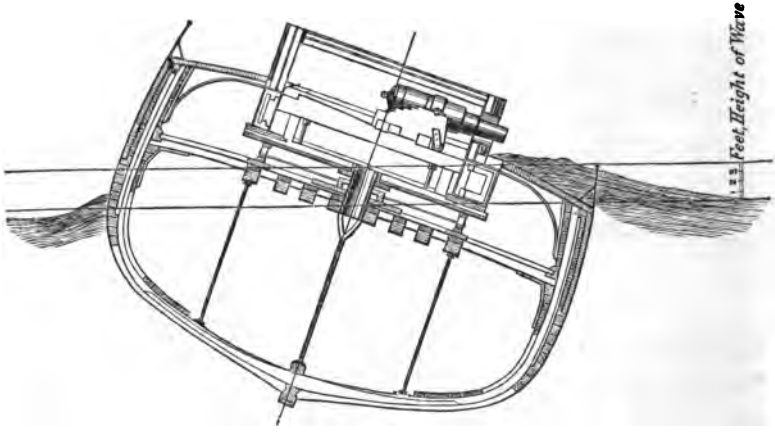



Fig. 55.




Digitized by Google

shield system, is attended by another advantage, viz., their transfer from the sides to the centre of the vessel. This is illustrated by fig. 55, which shows a shield ship inclined at a sufficient angle to bring her gunwale to the water, and yet carrying her guns and port some feet above it. Fig. 54 shows the "Favourite" of exactly the same height out of the water, inclined at the same angle, and yet burying her ports and guns in the sea.

'It cannot be necessary to add a word by way of enforcing the lesson taught by this illustration. It should be remarked, however, that the same causes which tend to disable the fighting of the guns in the "Favourite," while those in the "Naughty Child" remain perfectly fit for action, tend also, in a less degree, to give the latter superior steadiness when the two ships are rolling through less angles of inclination under ordinary circumstances.* The less a gun is moved about, the more accurate is its practice; and it is easy to see that the guns in the "Favourite" are moved through much smaller spaces than those in the "Naughty Child." This is an advantage not to be slighted in these days, when such costly efforts are made to improve our artillery practice, and fighting powers at sea.'

Since these remarks were made by Captain Coles, the author has been informed, of the truth of which he cannot pledge himself, that the turret of the 'Royal Sovereign,' which carries two 300-pounders, weighs, with its supports and other appliances, but without the guns, 162 tons, the guns giving 28 tons additional. It is obvious, therefore, that the 285 tons allowed for the 'Naughty Child' would have been, according to this statement, insufficient for two turrets and three guns.

In the early stages of this construction a turret was prepared by Captain Coles, and tested by several rounds from the 68-pounder smooth-bore gun. The results of this experiment were —according to information received from the Admiralty,— approved; but this test could not be considered conclusive, as only spherical cast-iron shot was used, and the large guns

* In the discussion which followed Captain Coles's paper, Mr. Reed denies that the guns of the 'Favourite' would be under water when the ship was rolling at an angle of 20°. On the contrary, he maintained that the ports of the 'Favourite' at that angle, 20°, would be clear of the water 1 foot 7 inches.

Digitized by Google

with steel bolts could not be tried, as they were not then in existence.

From the commencement of the war in America to the present time, the turret system of construction has been adopted by both belligerents in their river boats, with varied degrees of success; and in this country, and the maritime ports of Europe, the plan is not sufficiently matured to render it effective in all cases for large sea-going vessels. Great credit is nevertheless due to Captain Coles for the introduction of the revolving system, and for the perseverance with which he has laboured to bring it into notice, and to render it effective for general service. It yet remains to be seen, in this stage of the invention, what will be the ultimate result.

14. Mr. Alexander M'Laine, of Belfast, to whom we have already referred, suggests a great variety of improvements for a class of vessels calculated to work the guns *end on* in the line of the keel, and from which we make the following abstracts. In his second proposition he advocates 'that the twin screw system is eminently adapted for increasing the power and efficiency of vessels of war, and that vessels adapted for twin screw propellers should have double stern-posts.' That vessels should be constructed to fight *end on*, in order to expose a minimum of surface, and that large guns should be mounted on carriages to run on longitudinal deck railways.'

These are amongst the chief improvements suggested to the Admiralty by Mr. M'Laine. Many of them may be of questionable efficiency, but some of them are valuable and may be relied upon in regard to their ultimate results. The double stern-posts are, however, in use by the Admiralty in all the twin-screw vessels which they are building, and we have already seen that the 'end on' system of fighting large guns is already carried out in the 'Pallas,' 'Bellerophon,' 'Lord Warden,' and other vessels. On the subject of the combination of wood and iron in the construction of vessels, it will be noticed that we entertain anything but favourable opinions of the composite or mixed form of construction, and that for the reasons already assigned in regard to the strength of ships. Mr. M'Laine attaches great importance to the copper sheathing, and to attain that object he not only retains the plating with iron frames, but he builds

Digitized by Google

a wooden ship outside of the iron one for the exclusive purpose of having it copper-sheathed. Now, as regards strength, it must be admitted, that Mr. M'Laine's system, with the interior iron skin and the exterior ribs and frames, as shown at figs. 43, 44, 45, and 46, page 100, exclusive of the transverse frames of wood and planking, the ship is to all intents and purposes an iron structure. This being the case, it becomes a question of cost, in comparison with that of iron to the entire exclusion of wood, the iron armour-plate backing and deck only excepted. Mr. M'Laine's ideas of the composite construction are, however, of that high order of merit as to justify us in making the extracts and investigations which we have already given.

Irrespective of the composite construction, Mr. M'Laine recommends the double stern-posts for the twin screw propellers, as shown in figs. 56 and 57 with a single large gun at the stern on the fighting deck, and this arrangement, with the three railway guns on the forecastle, as shown in position on the section and plan, constitutes the armament of the ship.

In Mr. M'Laine's twelfth improvement in the construction of gun-boats or vessels with light draft of water, he recommends

Fig. 56.

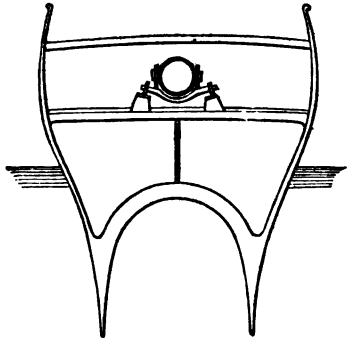
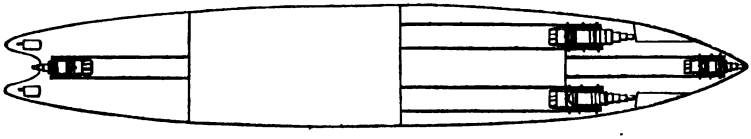


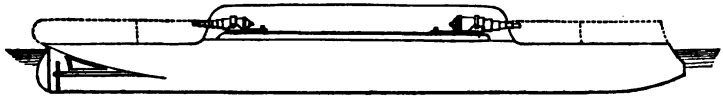
Fig. 57.



Digitized by Google

that they should be built for double screws, and armed with two large horizontal guns, as shown in the drawing, fig. 58.

Fig. 58.



15. Having briefly stated the different systems of construction recommended respectively by their different authors, we arrive at the conclusion, that much has yet to be done before the naval architect can decide, with any degree of certainty, what should be the description of vessels best adapted for purposes of war.

Armour plating is comparatively an untried system. The best form and size of these vessels, as well as the proper strength of their armour plates, have yet to be determined; and the best contrivances, and best designs of the present day, can only be considered approximate to what may ultimately be required to resist the impact of shot from large guns and other destructive agencies that have yet to be developed. The defects of our present constructions will have to be tested by actual war before the correct principle of construction is attained, and until that time comes—which we hope is far distant—we must be content to go on scheming about great guns and armour plates, till the powers of attack so much exceed that of defence, as to render—what is not improbable—*a clear open ship above the water-line*, of whatever burthen, safer and better calculated for security than one sunk to a great depth by an unbearable load of armour.

The Americans seem to have arrived at this conclusion from actual practice against forts and iron-clad ships, and state that heavy smooth-bore pivot-guns and spherical cast-iron shot are more than a match for any thickness of armour plates that a ship is able to carry; and it is further stated that smooth-bores, throwing solid spherical shot, are decidedly superior to rifled guns with their elongated bolts. The Federal Board of Ordnance observe in their report, 'that no manner or thickness of iron or

Digitized by Google

steel armour that could be carried on the hulls of ships will resist the impact of solid spherical shot, fired from the heaviest calibres of the navy at close range, with appropriate charges of powder.' And it is further reported, that one of the Federal admirals gives it as his opinion, 'that no ship can secure absolute immunity from heavy guns at short range,' and 'that the armour plates of ordinary ships will eventually terminate in the same manner as plate armour for cavaliers;' 'that the progress of science will limit the incumbrance of armour more and more narrowly to a vessel's vital parts, and that in the end it will probably be concluded, that upon a balance of advantages and disadvantages, a cruiser intended for sea-service had better carry no armour at all.'

These opinions appear to strengthen those at which we have arrived from the experiments witnessed on the different targets at Shoeburyness, and we have yet to learn to what extent a serviceable ship should be plated, or whether we should not adopt the opinion of the American admiral, and entirely get quit of the incumbrance, excepting only the protection of the hull. One thing appears quite certain, that a light well-equipped ship, with great speed and power, would outstrip another with a cargo of iron plates on her sides. Even supposing that these plates were to some extent invulnerable, which is not the case, it would then follow that such a vessel would be unable to overhaul and bring to action a more speedy and active manœuvring opponent. It is doubtless correct that an unprotected vessel would have no chance with the iron-clad within the destructive range of her guns, and if her sailing powers were superior she would, under all circumstances, be the safer and better ship of the two.

16. What we have to consider is, therefore, the construction of a light armour-plated ship with an average amount of sailing powers, calculated to manœuvre and bring the enemy to close quarters; nor is this an impracticable condition, for we find, from Admiral Porter's report on the bombardment of Fort Fisher, that the 'Monadnock,' a vessel of the 'Monitor' class, of moderate dimensions, had a speed of 13 or 14 knots per hour, which is not much short of that of the very best of our frigates, and that she outlived a terrific gale. Although armour plating, by its

Digitized by Google

great weight, tends to retard the motion of the ship,* yet it is, nevertheless, of great value, especially under circumstances where she may be struck with either shot or shell between wind and water. Most of our naval commanders can afford to lose a few men on deck, but they cannot afford to lose the ship; and to be sunk—'Alabama' fashion—by a single shot and to go to the bottom is not what is wanted in naval construction. These are grave considerations, and, under the impression that some modification of the principle of armour plating might be used without overburdening the vessel, a report (of which the following is a digest) was recently submitted for consideration to the Admiralty:—

MANCHESTER: *December* 9, 1864.

MY LORDS,—At the request of His Grace the Duke of Somerset, I have the honour to submit for your Lordships' consideration the following statement on the construction of iron ships of war:—

In the present state of our knowledge it is extremely difficult to ascertain what description of vessel is best calculated to meet the requirements of naval warfare. The changes are so rapid, and the results as to the ultimate strength of guns, weight of shot, &c. &c., so uncertain, as to prevent us arriving at—in this state of constant transition—any definite result for the guidance of the controller of the navy or the naval architect in the construction of ships. There is every reason, however, to suppose that rifled guns of great power and force will eventually compose the armament of ships of war, and that vessels adapted to this description of ordnance will have to be constructed to meet a new system of tactics, which must of necessity follow as a result.

The improvements in the manufacture of iron and steel now in almost daily progress are sure to lead to similar improvements in the construction of guns of increased range and power; but until that desideratum is accomplished, and the description of vessel determined upon as most destructive, in her powers of attack, it is in vain to think of arriving at anything definite as

* This is not always the case, as some vessels when more deeply immersed will gain speed when propelled by the screw, which has greater hold on the water; much, however, depends on the trim of the ship.

Digitized by Google

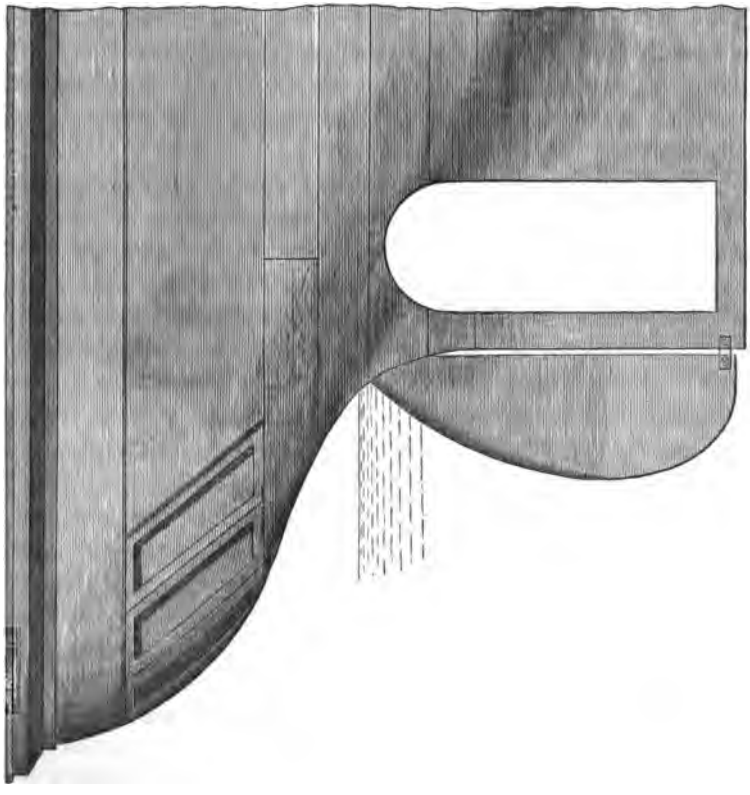
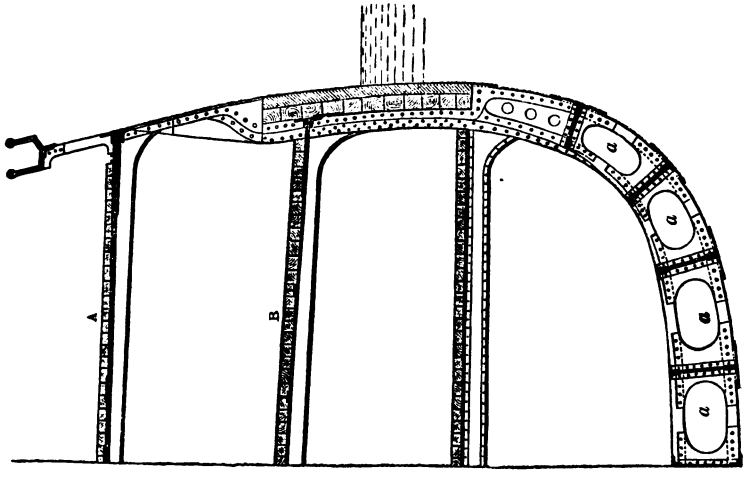


Fig. 59.

Midship Section.




Digitized by Google

regards the strength, form, and other considerations in the construction of ships. It is, therefore, impossible for your Lordships, or any other body—however intelligent—to determine the class of vessels best adapted to meet all the requirements of an effective service.

Assuming, however, that durable guns, say from 350 to 400-pounders, can be made from homogeneous iron or steel, and that these guns are the most effective and powerful that can be employed on board ship, it then follows as a question,—what description of vessel is the safest and most useful for the effective working of such an armament? To the solution of this question I have ventured to apply the knowledge I have acquired from long experience in the working of iron, and judging from what I have witnessed of the effects of heavy ordnance on iron armour plates, I am of opinion:

1st. That strong, well-built iron vessels, carrying from four to six 350 or 400-pounder guns—having fine lines and great speed—appear to be the class of vessels, which would form an important addition to our naval force.

2nd. That such vessels should be protected in the line of the neutral axis by a belt of iron armour plating, varying from three to five feet above and the same below the water-line, according to size, all round the ship.

3rd. That vessels of this class may be constructed with upper and fighting decks, as shown in section at A, fig. 59, or the upper deck A may be removed and the batteries confined to the main gun deck only, as shown at B. This construction with the upper deck removed—provided it can be dispensed with—would probably be preferable, as the ship would present a reduced area of surface to the enemy's fire, and thus render her more difficult to hit at a distance. In both constructions there would be no protection for the men at the guns; the sides in both cases to be only $\frac{5}{16}$-inch thick plates, and to admit a free passage through the upper bulwarks of the ship for both shot and shell.*

4th. That both descriptions of vessels should be constructed on the cellular principle throughout the whole length of the hull, as exhibited in section (fig. 59), with occasional water-tight

* The sides of the ship above the armour plate to be composed of tough plates, that will tear and not break into splinters from the passage of the shot.

Digitized by Google

bulkheads at convenient distances in the length of the ship. The keelsons marked *a*, *a*, *a*, &c., to run the whole length of the ship, and unite at the point of intersection as they converge upon the lines of the stem and stern. Also, that the transverse frames or ribs be 4 feet asunder, and that every sixth rib be plated and made water-tight in the cells between the exterior skin and the interior water-tight flooring. Above the lower deck the frames to be only 2 feet asunder, in order to give additional support to the armour plates and backing.

5th. As the object of this construction is not to prevent the entrance of shot and shell excepting in those parts of the hull where danger is imminent from the effects of heavy guns at close quarters, which an able and skilful officer will be careful to avoid, reserving to himself the choice of fighting with his ship at a distance where his armour cannot be penetrated, but where he nevertheless may be able to inflict damage by a rapid discharge of his large guns at long range upon the enemy, whose armament in this case is presumed to be inferior in power. This cannot be done, however, without speed, and hence the necessity of greatly increased power and a fine run fore and aft in the lines of the ship for the attainment of that object.

I venture to direct attention to the fact, indisputably established by the Shoeburyness experiments, that our strongest armour-plated vessels would not be able to resist the effect of the steel shot or shell of our largest guns at short range; but it must be admitted that the armour-plated ship has certain advantages, as the destructive effect of these shot depends upon the proximity of range, and an armour-plated ship might safely take a position which an ordinary ship could not take without incurring the risk of destruction. Entertaining these views, I respectfully submit for your Lordships' consideration the construction of a class of iron-plated vessels which might, under ordinary circumstances, form an important adjunct to the heavy armour-plated ships of Her Majesty's navy.

I have the honour to be,

Your Lordships' faithful servant,

WM. FAIRBAIRN.



Digitized by Google

In the foregoing statement the chief object the writer had in view was the construction of an iron ship, having its material so distributed as to secure a maximum of strength and security with a minimum weight of iron. Next followed the consideration of what appeared necessary to be accomplished to meet the force of heavy artillery, and to furnish additional security to the ship under the different conditions of defence and attack. It will be noticed that the paper neither advocates turrets nor guns at midships protected by armour plates. On the contrary, it provides, under certain conditions, for a perfectly clear fighting deck, with tough and carefully annealed plates for the sides, made sufficiently ductile to tear and not break into splinters from the effects of shot and shell, which in this case will have a clear passage through the ship between decks. It is further noticed that a reduced size of vessel is proposed—with probably a few exceptions—varying from 2,000 to 2,500 tons burthen, with the upper works as low as possible on the water, and these united to powerful propellers appear to be the class of vessels best adapted in many respects for the approaching new system of tactics which, to every appearance, 'looms in the distance,' and may arrive when least expected. In short, a *small ship, having great speed and large guns*, is, according to our views, *one* of the desiderata for an effective navy.

Reasoning from these facts, and from the effects of shot on iron armour plates, and assuming that guns varying from 350 to 600-pounders may eventually come into use, we arrive at the conclusion that ships of war, whether composed of iron or wood, would be equally safe, under certain conditions, if not safer, without than with a covering of armour plates at and above the fighting deck.

It has been fully established that steel shells and steel bolts from large guns will perforate plates from 6 to 8 inches thick, and if this can be done within moderate range, the iron-clad is no protection against the entrance of such unwelcome visitors. On the contrary, the iron armour plating is the very thing to arrest the progress of shot and shell, causing the latter to explode in the body of the ship. Another injurious effect produced by large guns on the sides of an iron-plated ship is, that in every case where the shot goes right through the armour

Digitized by Google

plate, it not only effects a passage for itself, but it carries along with it from the front a destructive portion of the plate, making a tremendous breach in the side of the ship. These facts are of great importance, when considered in relation to the construction of ships of war. In the case of non-iron-clad vessels, the shot in going through would do less damage than to one covered with armour plates, from the fact of the large pieces of armour plate, timber backing, &c., that are irresistibly carried forward with a through shot.

We have seen openings in some of the targets equal to five or six times the size of the shot from large guns, and this great increase in the size of the opening was entirely caused by large masses of the armour plate being driven forward through the backing and interior skin. It is evident that the same effect would be produced on the sides of a ship as on the target, and it therefore becomes a question for grave consideration, how far such plates should be used, and in what direction they should be applied for the safety of the ship and those on board.

Under the circumstances, it must be admitted that heavy armour plates in some cases really become a positive evil when the ship is within the destructive range of large guns. In our report to the Admiralty we have recommended the employment of armour plates entirely round the ship, five feet above and five feet below the water line, and doubtless this would be serviceable in protecting the hull at long range or at distances where the shot could not penetrate; but judging, as we have already remarked, from the effects produced on iron and wooden targets at a range of 200 yards, the armour-plated vessel would probably be more damaged by shot at short ranges than the unprotected ship.

17. Under certain conditions, armour-plated war ships possess decided advantages over those of the ordinary construction. As a basis of reasoning let us assume that both kinds of ships would be penetrated, and more or less broken up, by the shot from our most powerful guns at a range of 500 to 800 yards, and that at double this range the former would stand comparatively intact, whilst the latter would be destroyed. Now, for reasons already given, the ordinary war ship would have the advantage



Digitized by Google

over the other at the first range, but at the second 1,500 or 2,000 yards range the results would be reversed—that is, the ordinary ship would be destroyed by the shot, whilst the other with armour plates would be comparatively uninjured. The conditions we have assumed are not hypothetical, as the velocity of the shot would be considerably reduced in a range of 2,000 yards, as compared with about half the distance. In the bombardment of a fort, for example, the armour ship could safely discharge her cannon upon the fort at a distance of 2,000 yards, whilst the ordinary ship could not do so without incurring the risk of destruction in cases where heavy ordnance was employed. Again, in a sea-fight between two such vessels, carrying equally powerful armaments, at close quarters the ordinary ship might have the advantage, but the tactics of the commander of the armour-plated ship would be to fight his enemy at long range, that is, a range of from 1,500 to 2,000 yards, at which distances he could destroy an ordinary ship with safety to his armour ship; in this case the tactics of the commander of the ordinary ship would be to rush into close quarters, or to fire upon his enemy at or within the range of 1,000 yards; but in doing so, his vessel is liable to be destroyed by the shot of the armour ship before he has attained this proximity of range. Under such circumstances the best chance of safety for the ordinary ship is flight—a most obnoxious alternative to a courageous seaman.

It has hitherto been assumed that heavy armour-plated ships are necessarily defective in sailing qualities. Theoretically considered, we are certainly not warranted in making such a sweeping assumption; as this is a question more of practice than theory, we may venture to ask, Is the result of our experience sufficient to warrant us in concluding that *no form or size* of heavy armour-plated ships can be constructed with average sailing qualities calculated to meet those not burdened with armour? Now, if the report of Admiral Porter, before referred to, can be relied upon, we should infer that our assumption relative to the sailing powers of these ships is only based upon a limited range of facts. And, moreover, another important suggestion contained in the report on the bombardment of Fort Fisher, is that heavy armour-plated ships should, under

Digitized by Google

certain circumstances, be combined with broadside vessels capable of sustaining a rapid if not a continuous fire.

18. The destructive effects of large guns are difficulties not easily surmounted, and the question arises whether wood or iron is the best and safest material for building ships of war. On these points there are different opinions. Those in favour of iron maintain that the iron ship is much stronger, more durable, and less liable to take fire from shells than those of wood. On the other hand, the damage from shot passing through a wooden ship is not so great as in one constructed of iron, as the wood closes upon the aperture, whilst the other drives before it the plates and frames, and ruptures the rivets and joints. Iron vessels, however, present many advantages over those of wood, and decidedly so in those where the double bottom is carried round the hull to the height of the under side of the lower deck on each side. This form of vessel, if divided into sections by water-tight bulkheads carried from the bottom to the under side of the lower deck, would render the structure, to a great extent, secure from the effects of either shot or shell: and that effectually if surrounded with armour plating above and below the water-line, as recommended in a preceding chapter.

19. Another consideration in connection with the present movement in the naval arsenals is that of size and tonnage. If large and powerful guns are to be considered the most formidable weapons with which we have to contend, it would appear that strong well-built iron vessels of 2,000 to 2,500 tons burthen, carrying from 350 to 400-pounders, would be preferable to the 'Warrior' class, or those of larger dimensions.

It is evident from what we have seen of the 'Great Eastern,' that smaller vessels are handier, more easily worked, and with superabundant steam-power would manœuvre with a celerity superior to the larger description of vessels. Besides, if kept low in the water, they would be more difficult to hit; and another great advantage would be that in case of accident the loss would be less serious than that of a ship double the size, and with twice the number of persons on board. It would confirm the old proverb of not having 'too many eggs in one basket,' and ultimately prove that the smaller description of ships, with

Digitized by Google

equally heavy armament, would be equally, if not more, efficient in action than the larger class of vessels.

As regards rams, the present large frigates might be converted into vessels of this class. What is wanted for this purpose are powerfully constructed bows, weight, and momentum, and there is no mistake what the 'Minotaur,' and vessels of that class, could do in that way, if prepared for that purpose.

Digitized by Google

## CHAPTER VIII.

### ON THE PROPERTIES OF CAST AND WROUGHT IRON AND STEEL AS MATERIALS FOR THE CONSTRUCTION OF ORDNANCE.

1. The experiments instituted and conducted by the Iron Plate Committee enabled them to discover various defects in the composition of iron armour plates, and to recommend to the different manufacturers the changes necessary to be introduced for improving the quality of the iron as regards its tenacity, ductility, &c., and its powers to resist the impact of shot. These recommendations were carefully attended to on the part of the manufacturers, who at once commenced the changes necessary to meet the wishes of the Committee, and by careful attention and a determined and energetic perseverance they have brought the manufacture of iron to a degree of perfection, especially as regards its powers of resistance to projectiles, seldom if ever excelled. Plates that were brittle, unsound, and imperfect in many respects, are now rendered solid, ductile, and in every way satisfactory; and the greatest praise is due to the manufacturers for the way in which they have improved and elaborated the process of welding, rolling, and working the large masses of iron required for defensive armour.

At the commencement of the manufacture there was no machinery in existence that could roll plates above 10 feet long, 3 feet wide, and 3 inches thick: in fact, most of the armour-plates which cover the sides of the 'Warrior' were forged piece-meal under the hammer; but they are now rolled from 20 to 24 feet long, 4 feet wide, and 8 to 10 inches thick, with a degree of certainty and precision which renders them more uniform and stronger in their powers of resistance to the force of impact than they were at the commencement of the process. There is now no difficulty in manufacturing plates of any required dimensions, possessing all the qualities essential to the plating of iron ships and forts. We have referred to these facts to show that the

Digitized by Google

improvements in the manufacture of armour plates apply also to that of ordnance, which is now constructed of the same material, including that of homogeneous iron or steel bored out of the solid for the barrel.

2. It has been stated that, during the civil war now so fiercely contested between the Northern and Southern States of America, the iron of those countries is very superior to that of Great Britain, and that it is better calculated for the manufacture of guns and shot than anything of the same kind produced in this country.

We have been at some pains to ascertain the truth of this statement, and having received certain official documents from Major Wade, who conducted a long and interesting series of experiments 'On the Strength and other Properties of Metals for Cannon,' we are the better able to form a correct judgment on the subject.

The experiments were made at the request of the Ordnance Department of the United States, in order, as stated, to procure information required in the arrangement and improvement of the system of military monitors and artillery for the land service; and that body could not have selected a more intelligent and talented officer to conduct the experiments than Major Wade. In durability and economy it was considered that cast iron was the best material then known for cannon; but experience had proved to the United States, as well as to this country, that the endurance of cast-iron cannon could not be relied upon, and hence followed the experiments, some of which it will be profitable to notice in so far as they bear directly on our own manufacture.

The experiments were made 'to determine the transverse strengths of different kinds of cast iron, and of the same kinds cast under different circumstances of temperature and of exposure in fusion.' In these experiments, Major Wade remarks, that the results are not of a strikingly marked character. A high temperature of casting appears to be beneficial both for strength and soundness. Casting at low temperatures he found injurious, as it produced cavities in the casting. The results were not, however, entirely free from anomalies, but they nevertheless showed a positive increase of strength as the iron is continued in fusion for longer periods of time. The same results were observed in our own experiments derived from repeated meltings, and to which we have referred for comparison.

Digitized by Google

Major Wade gives the results of iron prepared for the casting of a 10-inch gun, from which he selected several bars 2 feet long out of the same parcel of iron in all the different stages of the second and third fusion, from the first melting of the pigs up to the casting of the gun. The following is a summary of these results:—

SECOND FUSION.

| | Strength | Ratio |
|---|---|---|
| First casting, made as soon as the pig iron was melted | 6,506 | 1,000 |
| Second casting, iron in fusion one hour . . . | 7,316 | 1,124 |
| Third casting, iron in fusion two hours . . . | 8,256 | 1,269 |
| Fourth casting, iron in fusion three hours . . . | 8,378 | 1,287 |

THIRD FUSION.

| | | |
|---|---|---|
| Seventh casting, iron in second fusion 1¾ hours, whole time in fusion 4¾ hours . . . . . | 10,411 | 1,600 |

From this it appears, that the cohesive strength of the iron in so far as it can be shown by its power to resist a transverse strain, is increased sixty per cent. by its continued exposure to fusion for a certain number of consecutive hours. On this question it may be interesting to compare the results of the American irons with those of this country, and taking the transverse strengths of some of the different irons experimented upon including those taken from repeated meltings, we have the following summaries of results:—

AMERICAN IRON.

| Description of Iron | Hours in Fusion | Breaking Weight of 2-inch square Bars 20 inches between Supports | Unit of Strength | Remarks |
|---|---|---|---|---|
| | | lbs. | | |
| Franklin iron, original pig, first fusion . . . . | ... | 9,846 | 6,146 | |
| Franklin iron, second fusion . | 2⅔ | 13,950 | 8,675 | |
| Franklin iron, third fusion . . | 3 | 16,772 | 10,069 | |
| Amenia furnace, second fusion . | 3 | 15,525 | 9,322 | |
| Richmond furnace, second fusion | 2 | 15,525 | 9,322 | |
| Gartsherrie furnace, second fusion | ... | 9,846 | 5,970 | |
| Mean | ... | 13,569 | 8,250 | |

These bars were each 24 inches long, supported at both ends, the breaking force applied in the middle; distance between the supports 20 inches. The unit of strength represents the

Digitized by Google

weight, in pounds, required to break a bar one inch square, supported at one end; the weight being applied at a distance of one inch from the point of support.* For square bars it is determined by this formula: $\frac{l\,w}{4bd^2} = s =$ the unit of strength; $l$ being the length between the supports; $w$ the breaking weight; $b$ the breadth of the bar; and $d$ its depth. For circular bars, ·58905 $d^3$ is substituted for $bd^2$; $d$ being the diameter.

For comparison we now give the results of experiments on some of the irons of Great Britain, reduced to the same standard as the American iron in the foregoing table.

IRONS OF GREAT BRITAIN.

| Description of Iron | Breaking Weight of 1-inch square Bars 4 feet 6 inches between the Supports | Breaking Weight of 4 feet 6 inch Bars reduced to 2-inch square Bars 20 inches between the Supports | Unit of Strength of Value of $S$ | Remarks |
|---|---|---|---|---|
| Pontypool cold blast . | 581 | 12,569 | 7,843 | |
| Low Moor . . . | 483 | 10,432 | 6,520 | |
| Coedtalon . . . | 424 | 9,158 | 5,724 | |
| Staffordshire hot blast . | 392 | 8,467 | 5,292 | |
| Mean | 470 | 10,116·5 | 6,344 | |
| Eglington iron, hot blast, from repeated meltings: | | | | |
| Mean of 8 meltings. | 445 | 9,612 | 6,007 | |
| „ 9th melting | 547 | 11,815 | 7,384 | |
| „ 10th „ | 567 | 12,247 | 7,654 | |
| „ 12th „ | 692 | 14,947 | 9,342 | |
| „ 16th „ | 381 | 8,229 | 5,143 | |
| Mean | 526 | 11,370 | 7,106 | |

Having reduced the above irons to the same standard of value, it will be observed on comparing the two tables, that the maximum of the American irons, after the treatment of second and third fusion, possesses greater tenacity per unit of strength than the Eglington† after the sixteenth melting; the ratio being as

* This unit of strength, or the value of $S$, is the modulus of ultimate strength of the material.

† It must be noticed that the Eglington is one of our weakest irons, and was not prepared for the casting of guns. Had it been prepared by mixture for gun metal the results in all probability would have been more favourable.

Digitized by Google

1 : ·9277 or nearly $\frac{1}{11}$th stronger. A still greater disproportion is observable, if we take the mean of the American experiments and compare them with that of the Eglington remelting, and the ratio is found to be as 1 : ·837, which indicates a considerable diminution of strength in the English irons as compared with the gun metal of America.

It will, however, be noticed, that the comparison here given is not made with our best prepared gun metal, but with the irons in common use in this country and with the Eglington Scotch iron, which is a fluid but not a strong adhesive metal. It must nevertheless be admitted, that none of the irons of this country will stand the same tests as those given by Major Wade, nor are we prepared to state what improvements may be effected by retaining the metal in a state of fusion from three to four hours in the same way as done by Major Wade. Granting, however, that the American irons have the advantage of a tenacity of one-sixth to one-seventh above the best irons of this country, we are nevertheless of opinion, that their cast iron is not the best, nor yet the strongest material for the manufacture of guns of large calibre. Of this we have a striking example in the bursting of a considerable number of these guns, and as proof of their dangerous character, we may instance the bursting of several at the siege of Fort Fisher, Wilmington, when more than forty lives were sacrificed by the bursting of six cast-iron Parrot guns.

It is true, that every possible care is taken to have the guns of sound metal by the system of casting them hollow, as generally practised in America. And as this process is not without interest, and assuming it to be useful for other purposes besides that of guns, we may be excused for giving a brief description of it. Major Wade in his report of the manufacture and proof of 8-inch and 10-inch Columbiads cast at Fort Pitt, by Messrs. Knap & Co. in 1851, states, that 'Two 8-inch Columbiads were cast, July 30, 1851. The iron used was made at Greenwood Furnace, New York, and was of the following qualities, viz.: $\frac{36}{100}$ of No. 1; $\frac{25}{100}$ of No. 2; and $\frac{39}{100}$ of No. 3; 28,000 lbs. were melted in two furnaces (12,500 in one, and 15,500 in the other), about $\frac{3}{4}$ of which was of 2nd fusion, and $\frac{1}{4}$ of 3rd fusion.

Digitized by Google

The Columbiads, therefore, consist of about three parts of 3rd fusion, and one part of 4th fusion.

'After melting, the liquid iron remained in the furnaces 2½ hours, exposed to a high heat, and was then discharged, by separate streams, into a common reservoir, at the same time. It was withdrawn from the reservoir in a single stream, which, after proceeding a few feet, separated in two branches, each leading to a separate mould, filling both moulds at the same time.

'Both of the moulds were placed in open pits; one of the castings was made solid, and cooled in the usual manner, without heating or covering the pit; the other was cast hollow, by means of a core formed on a tube of cast iron, through which a stream of water constantly circulates while the iron is cooling. The core tube is water-tight, and is closed at the lower end. The water is conducted to the bottom of the core through an interior tube placed in the centre of the core, and open at its lower end. It ascends through the annular space between the two tubes, and is discharged from the core at a point above the casting, and flows off in a heated state.

'A fire was kindled in the bottom of the pit, directly after casting, and was continued 60 hours. The pit was covered, and the iron case containing the gun mould was kept at as high a temperature as it would safely bear, being nearly to a red heat all the time.

'The water passed through the core at the rate of 2½ cubic feet per minute, or 150 feet per hour. At 25 hours after casting, the core was withdrawn, and the water thereafter circulated through the inner cavity formed by the core, at the same rate, for 40 hours; making 65 hours in all. The whole quantity of water passed through the casting is nearly 10,000 cubic feet, weighing about 300 tons, or about fifty times the weight of the casting. The heat imparted by the casting to the water, and carried off by the latter, is equal to 6° on the whole quantity of water used.

'Two 10-inch Columbiads were cast August 21. Greenwood iron, of the same qualities as melted for the 8-inch guns, was used. About $\frac{1}{9}$ consisted of 1st fusion; $\frac{5}{9}$ of second fusion; and

Digitized by Google

$\frac{1}{3}$ of 3rd fusion. It was melted in three furnaces, containing 12,000, 15,000, and 19,000—in all, 46,000 lbs. The liquid iron remained in fusion $2\frac{1}{4}$ hours, and was discharged from all the furnaces at the same time into a common reservoir, from which it issued in a single stream, and was conducted to the bottom of the gun pit, where it branched off, and entered the lower ends of both moulds at the same time.

'Both moulds were placed in the same pit. One of the guns was cast solid, the other was cast on a hollow core, and cooled within, by a stream of water circulating through it, as before described. All of the space within the pit, outside of the moulds, was filled with moulding sand, and rammed. This was done because the iron cases of the moulds were not large enough to admit the usual thickness of clay in the walls of the mould. It was apprehended that the heat of the great mass of iron within would penetrate through the thin mould, and heat the iron cases so much as to cause them to yield and let the iron run out of the mould. Consequently, the exterior of the mould of the 10-inch hollow gun, instead of being exposed to heated air while cooling, as was the case in the 8-inch hollow gun, was surrounded by green sand, which caused a more rapid cooling of the exterior surface of the casting.

'Water was passed through the core at the rate of about 4 cubic feet per minute, or 240 feet per hour, for 94 hours, amounting in all to 22,560 feet, weighing about 700 tons, or seventy times the weight of the casting. The mean elevation of temperature of all the water passed through the core, in 94 hours, was about $3\frac{1}{2}°$. At the end of this period, an attempt was made to withdraw the core from the casting, which proved unsuccessful. The contraction of the iron around it held it so firmly, that the upper part of it broke off, leaving the remainder imbedded in the casting. The stream of water was then diminished to about 2 feet per minute, which continued to circulate through the core for 48 hours. The supply of water allotted to and circulated through both the 8-inch and 10-inch guns was equal in weight to the weight of each casting, in about 1 hour and 20 minutes.'

In the following months of August, September, and October, the guns were finished, and being suspended by iron rods on

Digitized by Google

strong triangular frames, the proofs commenced, as stated by Major Wade, as follows:—

PROOF CHARGES.

8-inch { First fire—12 lbs. powder, 1 ball and sabot, 1 wad.
Second fire—15 lbs. powder, 1 shell with sabot.

10-inch { First fire—20 lbs. powder, 1 ball and sabot, 1 wad.
Second fire—24 lbs. powder, 1 shell with sabot.

SERVICE CHARGES.

8-inch—10 lbs. powder, 1 ball with sabot.
10-inch—18 lbs. powder, 1 ball with sabot.
Weight of 8-inch balls, 63½ lbs.; of shells, 48½ lbs.
Weight of 10-inch balls, 124 lbs.; of shells, 91 lbs.

The powder was all of Dupont's manufacture, 1837. The mean proof-range of that used in firing the 8-inch guns was 297½ yards; and of that used in firing the 10-inch was 299 yards.

The guns laid on the ground, when fired with the proof charges; and were then placed in the suspending harness, where they remained during all the firing with service charges.

The number of fires made from each gun, including the proof charges, was as follows, viz:—

8-inch gun, No. 3, cast solid, 73 fires.
8-inch gun, No. 4, cast hollow, 1,500 fires.
10-inch gun, No. 5, cast solid, 20 fires.
10-inch gun, No. 6, cast hollow, 249 fires.

Each of them, excepting the 8-inch gun, No. 4, cast hollow, burst at the last fire; and that remains unbroken, and apparently capable of much further service.

Two of the guns which burst, split through the breech and reinforce, in nearly equal parts, the fracture diverging about the trunnions, and terminating on opposite sides of the chase; leaving the latter with the muzzle, in one piece, almost entire. The 10-inch gun, No. 5, separated into two pieces only. The plane of fracture is nearly parallel with the trunnions; the lower part of the breech and reinforce remains unattached to the chase; the upper part, weighing 4,400 lbs., was thrown upward, and fell in the rear, about 80 feet distant. In its flight, it broke the limb of a tree, on a hill-side, 60 feet above the level of the gun when fired. The plane of fracture

Digitized by Google

in the 10-inch gun, No. 6, is through the vent, and extends forward into the chase, when it branches off towards the neck. The fracture of the 8-inch gun, No. 3, is diagonal, between the vent and trunnions.

It will be noticed that the 8-inch gun, cast solid, burst after the 73rd fire, while the same gun, cast hollow, sustained 1,500 fires before bursting. Similar, but different results as regards the number of charges, were obtained from the 10-inch gun, which burst with only 20 fires in the one cast solid, and 249 for that cast hollow.

3. These results exhibit marked differences in the endurance of the guns, and in order to render the results more apparent, it will be necessary to consider the causes from which to trace the differences which ensued in the cases of rupture.

It has been shown that the strain produced on any material by the action of a central force, diminishes as the squares of the distance from the centre increases. The demonstration of this hypothesis is based upon the idea that the area of the cross section of the body to which the force is applied remains the same before and after the application of that central force. So that, according to Barlow, if $r$ = radius of bore, R = radius of exterior, $b$ = increase of interior radius, and B = that of exterior radius, we shall have the equation $\pi(R^2 - r^2) = \pi\{(R + B)^2 - (r + b)^2\}$, or $R^2 - r^2 = R^2 + 2BR = B^2 - r^2 - 2br - b^2$; but since B and $b$ are very small fractions of R and $r$, their squares may be neglected, and we shall have $BR = br$ (3). But the strains produced on any two pieces of the same material will be proportional to the increase in length divided by the original length of each respectively—the absolute strain, for a given increase in length, depending on the co-efficient of elasticity of the material strained; so that if $\frac{B}{R}$ = the strain on the exterior, the $\frac{b}{r}$ = that on the interior; but if, in equation (3), we multiply and divide the first member by R, and the second by $r$, we shall have $R^2 \frac{B}{R} = r^2 \frac{b}{r}$, or the proportion $R^2 : r^2 :: \frac{b}{r} : \frac{B}{R}$, or the strain diminishes as the square of the distance from the centre increases.

Digitized by Google

And again, according to Rodman, let us suppose a gun perfectly free from strain, and apply a central force until the interior is brought to the breaking strain; and let the radius of the bore be the unit of measure, and $a$ = tensile strength of the square unit. Then, if the gun be one calibre in thickness, the distance from the centre of the bore to the exterior will be 3, and the strain will diminish, in obedience to the above demonstrated law, until that at the exterior will be $\frac{1}{3}$th of that at the interior, and the effective resistance which the gun will be capable of offering to a central force will be the sum of all these strains. In order to determine this sum let it $= u$, and let $x$ = any variable distance from the centre, and we shall have, for the strain upon any one of the infinitely thin cylinders of which the thickness of the gun is composed, $a\frac{dx}{x^2}$, and for the sum of all these strains, $u = a\int\frac{dx}{x^2} + c = -\frac{a}{x} + c$; now, to determine the value of $c$, let $u = 0$, and $x = 1$, (since when $x = 1$, the sum of the strains $= 0$), and we find $c = a$, and $u = -\frac{a}{x} + a$; and integrating between the limits $x = 1$, and $x = 3$, we have $u = a - \frac{a}{3} = \frac{2}{3}a$; or, the effective resistance of a gun one calibre in thickness will be $\frac{2}{3}$ of that which half a calibre in thickness would offer, if the strains were all equal as in tensile strain.

The above results suppose the gun to be entirely free from strain before the application of the straining force, a condition which could only be obtained by allowing it an infinite length of time to cool. For it never could cool without allowing the surface to fall to a temperature below that of the interior of the metal; and, since iron diminishes in bulk as its temperature decreases, it follows, that a gun cast solid, and cooled, of necessity, from the exterior and in a limited time, will be thrown upon a strain—the exterior being under a force of compression, while the interior is under one of elongation; and the greater the difference of temperature between the exterior and interior during the process of cooling, or the more rapidly the cooling is effected, the greater will be the strain.

Digitized by Google

Now, let us suppose a central force applied to a gun thus strained, and bear in mind the law of strain, as above demonstrated: the interior is already under a force of elongation, while the exterior is under one of compression; the action of the central force developes (in a gun one calibre thick) *nine* times the strain on the interior that it does on the exterior, *independent of previous strain*: so that we have the effort of the exterior to free itself from the force of compression to which it has been subjected in cooling, combined with the central force, to break the interior; and the wonder is, that guns thus strained in cooling endure as long as they have been found to do.

Mr. Rodman states that the less endurance of the 10-inch hollow gun than that of the 8-inch hollow one is accounted for by the fact that the 10-inch gun had no fire on the exterior of the flask while cooling, it having been rammed up in the pit, where it was supposed, at the time of casting, the heat of the gun would have been retained by the sand, until the interior should have been cooled by the circulation of water through the core-barrel.

This supposition was found to be erroneous on digging out the sand, as its temperature was found to be much lower than had been expected.

The less endurance of the 10-inch solid gun than that of the 8-inch solid one is, therefore, attributable to the increased strain to which it was subjected in cooling, arising from its increased diameter; and to the greater pressure of the gas in firing, which is, directly, as the diameter of the bore; since the weight of the shot increases as the cube of the diameter, while the area of its great circle, or the surface pressed, only increases as the square of the diameter.

The difficulties against which the engineer has to contend in the cooling of metals have been long known, and it is found next to impossible to determine any fixed law or estimate of the amount of strain inherent in metals as they pass from the fluid to the solid state. Much depends upon the mass, rate of cooling, form, and conditions under which the castings are made; and of this we have the most striking examples in the American Columbiad guns, which, under the charge of Major Wade, exhibit results of the utmost importance in regard to their



Digitized by Google

endurance, and the means adopted to procure uniformity in the law of contraction and expansion during the process of cooling. These experiments become the more important as they apply with equal force to other castings besides those for ordnance; and to show the wide difference which exists between one description of casting and another we, may again shortly refer to Major Wade's investigation.

The extraordinary endurance of the 8-inch Columbiads shows that the metal from which they were cast was of the best and strongest quality, as shown by the following mechanical tests:—

| | Density | Tenacity | No. of Fires endured |
|---|---|---|---|
| Cast and proved in 1851 . . | 7·287 | 37,811 | 72 |
| Cast in 1846, and proved in 1852 { | 7·247 | 29,423 | 2,582 |
| | 7·220 | 22,989 | 800 |

The form, dimensions, weight, method of casting and cooling, and the manner of proving, were the same in all. It will be seen that the gun made of the strongest iron, with a short interval of time between its manufacture and proof, endured the smallest number of rounds; and that those made of weaker iron, but proved long after they were cast, endured the greatest number of rounds. This remarkable feature in these trials suggests an inquiry as to the cause of such anomalous results.

The following table exhibits an account of all the experiments

TABLE III.—EXTREME PROOF AND ENDURANCE OF CANNON.

| Date of Proof | Description of Cannon Proved | Interval between Casting and Proving | Test of Gun-head Samples | | No. of Fires endured | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Service Charges in Guns cast | | Extra high Charges in Guns cast | | |
| | | | Density | Tenacity | Solid | Hollow | Solid | Hollow | |
| 1849 | 8-inch Columbiads | 34 days | 7·222 | 27,569 | 84 | | | | |
| | | | 7·233 | 27,531 | .. | 250 | | | |
| 1851 | 8-inch Columbiads | 30 days | 7·292 | 37,961 | 72 | | | | |
| | | | 7·287 | 37,638 | .. | 1,500 | .. | .. | Not burst |
| 1851 | 10-inch Columbiads | 49 days | 7·273 | 40,457 | 19 | | | | |
| | | | 7·306 | 41,952 | .. | 248 | | | |
| 1852 | 32-pounder cannon | 110 days | 7·271 | 33,590 | 1,000 | .. | 6 | | |
| | | | 7·281 | 34,307 | .. | 1,000 | .. | 21 | |
| | Mean of tests, and total endurance . . . . . | | 7·271 | 35,126 | 1,175 | 2,998 | 6 | 21 | |
| 1844 | 8-inch Columbiad | 100 days | 7·276 | 26,367 | 731 | | | | |
| | 10-inch Columbiad | 100 days | .. | .. | 600 | .. | 12 | | |
| 1852 | 8-inch Columbiad | 6 years | 7·247 | 29,423 | 2,582 | .. | .. | .. | Not burst |
| | 8-inch Columbiad | 6 yr. 44 dy. | 7·220 | 22,989 | 800 | | | | |

Digitized by Google

made in casting guns solid and hollow, in pairs, and of the mechanical tests, and the endurance of each in extreme proof; also of the extreme proof of other guns of the same model, not cast for experiment.

4. In a former part of this chapter the character and the effects of the strains which occur in the cooling of iron, when cast in large masses, are stated and discussed. But now it appears, from the results obtained in the trials since made, that there is another question to be considered—that is, the longevity of such strains, or the length of time during which a body will remain under a strain without a renewal of the straining force.

It is assumed that any casting or any other solid body will, if constantly strained for a long time, adapt itself, in part at least, to its strained position, and lose its power of regaining its original position.

Suppose, for example, that a proof-bar of cast iron be strained in the testing-machine until its deflection is about two-thirds or three-fourths of that which it will endure without breaking, or until the deflection nearly reaches the point at which incipient molecular separation occurs, and that the pressure be then removed: it will be found that the bar has acquired a small measure only of permanent set. But if the pressure be not removed—or if it be removed, and then again applied and continued a long time—it will be found that the bar had acquired a permanent set nearly equal to its deflection, and that its power of restoring itself to its original position has been almost entirely lost. Its particles, it would seem, have adjusted themselves to their new and constrained position, and become free, or nearly so. It appears that they resist constraint, and retain the power of self-restoration, for a short time only; but if the restraint be long-continued, they gradually conform themselves to it, and become passive or acquiescent.*

A bar which has thus been made to acquire a large permanent set, it is believed, has lost but a small portion of its power to endure renewed strains. It may be again pressed with a similar force, and acquire an additional deflection and permanent set

* See Mr. Fairbairn's paper 'On the Effects of Impact, Vibratory Action, and Long-continued Changes of Load on Wrought-iron Girders,' *Philosophical Transactions*, Feb. 7, 1864.



Digitized by Google

nearly or quite equal to that which had before been imparted to it. By repeating this process at long intervals of time, the permanent set of a bar may be extended much beyond the deflection which it was capable of enduring when it was first strained.

The strain produced in cannon by unequal cooling, as described by Major Wade, is one of compression on the exterior circumference, and of elongation on the circumference of the bore. It may be likened, as he judiciously remarks, to the strain which would exist in a hollow cylinder if the latter be cut through its thickness in one of its elements, and the fissure be afterwards enlarged by a mechanical force acting against the surfaces of the fissure. A strain thus produced would obviously stretch the interior surface of the cylinder, and compress its exterior surface. Now, if we suppose a strain of this kind to be so far extended as to approach nearly to the point at which incipient molecular separation occurs, any considerable addition of a central force of any kind will evidently produce rupture. This is, I believe, the condition of cannon when under a strain caused by unequal cooling; and as the force of fired gunpowder acts in the same direction, a few rounds, if made soon after casting the cannon, will be sufficient to burst it.* But if the same cannon be allowed a sufficient time between the casting and proving to free itself from strain, it will endure a number of rounds proportioned to the tenacity of the metal from which it is made. What length of time may be required to free a gun from strain can be ascertained only by experiment; but it will doubtless be found to be proportioned to the hardness and tenacity of the iron and to the bulk of the gun. Hard strong iron contracts most, and consequently is most strained, and will require the longest time to relieve itself.

5. We have already adverted to the endurance of wrought iron subjected to severe strains, and assuming that time is an element in the endurance of every kind of material when subjected to strain, the same question arises in regard to guns as apper-

* This applies to the fact that most of the 13-inch mortars cast at the commencement of the Crimean war were bored almost immediately after coming out of the foundry. The results were that a great number burst with the service-charge of powder after a very few rounds.

Digitized by Google

tains to beams, viz.: How many successive strains from charges of gunpowder will the former stand before fracture ensues? It is obviously correct that strains often repeated ultimately tend to rupture; and it appears evident that we cannot with impunity continue these forces unless we are prepared to incur the risk of fracture. It is therefore necessary in homogeneous metals—and in cast iron in particular—to ascertain as nearly as possible the law of endurance, and the means requisite to be employed to attain that desideratum.

6. Some attempts were made in this country to cast our heavy ordnance hollow, on the American principle; but the introduction of wrought and homogeneous metal and steel rendered the use of cast iron in the manufacture of guns no longer necessary. We may, however, refer to five experimental cast-iron 24-pounder guns, cast at Warrington, under the direction of the author, in 1855. The iron of these guns contrasts rather more favourably with the American metals, although it must be admitted that the American irons have the preference of increased density and increased tenacity over those of this country in the ratio of about 1 : ·95—or, in other words, the American iron is $\frac{5}{100}$ parts stronger.*

The information given in these pages would have been more complete if we could have given in detail the present improved state of rifled ordnance, as manufactured by the different makers and inventors. We have not less than five or six claimants for as many different kinds of guns. They have each their own peculiar mode of construction; and as they are, and have been, almost continually improving and changing their plans and material of manufacture, it would be an endless task to attempt a description of what has been done and is now doing. All that we can do is to give a short outline of the material and its adaptation as applied by the different makers, and leave to abler hands, or to the makers themselves, to work out the construction according to their own individual views and the efficiency of their respective guns.

7. For a series of years past, and up to the time of the Crimean war, when His Majesty the Emperor of the French first introduced the new system of protecting the sides of ships with armour, the

* *Vide* Appendix I.

Digitized by Google

Board of Ordnance and the Admiralty of this country never lost sight of the advantages of having the armament of the Navy of greatly increased power and weight. These advantages were confirmed by the introduction of the 68-pounder cannonades, and the difficulty of penetrating armour-plates led to an entirely new description of gun-construction, which, for these purposes, has to a great extent superseded the 68-pounder. This gun was, however, a powerful and effective weapon, but it was deficient in range and velocity; and to obviate these difficulties, and prepare for an entirely new system of naval warfare, the Government gave every encouragement to inventors for guns of long range and precision of fire.

Captain Blakeley, Mr. Whitworth, and Mr. (now Sir William) Armstrong were the first in the field, but only as experimenters —Mr. Whitworth on the small-arms rifle, and Captain Blakeley and Sir William Armstrong on the construction of 10 or 12-pounder wrought-iron rifled guns, the latter of which were submitted to the Government, and were highly approved. The result of this was a C.B. and a knighthood, accompanied with the office of ordnance constructor, to Mr. Armstrong. At Elswick and Woolwich an immense number of guns were manufactured, varying from 12 to 600-pounders, under his superintendence.

Sir William Armstrong's guns have all, until recently, been constructed on the coil system, which may be described as follows: The barrel is formed of wrought-iron bars wound spirally round a mandril. They are then welded in a furnace erected for the purpose, turned and hooped, until the required thickness and strengths are obtained. The hoops are of different thicknesses, according to position, and they are carefully bored and turned, in order to fit with great exactitude and give the due proportion of resistance to strain. In Sir W. Armstrong's manufacture the hoops are shrunk on to the barrel. Mr. Whitworth, however, adopts a different system, and depends entirely upon the accuracy of his fittings. The homogeneous barrel in this case is made slightly conical, and the hoops are forced on by hydraulic pressure to a uniform state of tension.

Large and powerful hoops—one, supporting the trunnions, is fixed near the centre of gravity to balance the gun, and the

Digitized by Google

others, after being carefully bored and turned—are fitted round the breech and the muzzle; it is then built up in the shape of a gun, and being bored, turned, and rifled, is ready for service. This may be taken as a brief description of the Armstrong gun; but, owing to occasional flaws in the welding of the spiral coils, it has been found necessary to adopt Mr. Whitworth's plan, and, in place of the coils, to introduce a perfectly homogeneous barrel of steel, and then hoop with wrought or homogeneous iron, in the way already described.

Mr. Whitworth's system has always been to bore the barrel out of the solid, and he adopts this method in every description of gun which he manufactures. He then hoops, as already described, with the same if not greater exactitude, all his heavy guns, and thus attains a uniformity of strain calculated to equalise and increase the resisting powers of the structure. In the smaller description of ordnance the hoops are dispensed with, excepting only for the trunnions, which encircle the barrel near the centre of gravity, as referred to above.

Captain Blakeley, Mr. Mackay, and others follow the plan of introducing the solid barrel and the subsequent process of hooping; but a number of Captain Blakeley's guns of wrought iron have been entirely forged and welded by Mr. Clay, at the Mersey Forge, Liverpool, and bored from the solid. It is, however, now found that the homogeneous steel barrel carefully hooped is a preferable and safer instrument for purposes of war than either the cast or the forged wrought-iron gun.

Captain Palliser, in order to make use of the present existing guns of cast iron, such as the 68-pounder, has introduced a system of lining the bore with a homogeneous barrel of steel. This not only increases the strength of the gun and removes part of the strain from the cast iron, but it enables him to apply the rifling principle, so as to increase the range and powers of penetration of the gun when fired against iron armour-plates.

Under all these forms of construction, it becomes a question for consideration whether or not the Bessemer system of manufacture of steel can be applied to the casting hollow guns under hydraulic pressure, so as to give increased density and tenacity to the metal, and entirely to dispense with the system

Digitized by Google

of hooping, which is both expensive and insecure. With a properly-constructed and a well-regulated hydraulic apparatus, much may be done in this way; and by adopting the American system of cooling, affording to the molten mass a free arrangement of the particles for adhesion in its molecular construction, a much stronger and very superior class of ordnance may probably be introduced. It has been stated that castings for guns are greatly improved by keeping the metal in a state of fusion for a number of hours before casting, and in order to equalize the strains arising from unequal contraction—one part cooling before another—it may be desirable to allow time for a more perfect adjustment of the crystals, as exhibited in the American experiments to which we have referred. Supposing that the Bessemer steel, when passing from the fluid to the solid state, follows the same law in its crystalline formation as cast iron, we then arrive at the important conclusion that as much time as possible should be allowed to the process of cooling, in order to obviate the unequal strains of contraction which pervade to a greater or less degree every description of crystalline structure.

Independent of the Bessemer system of casting steel into ingots, great advantages would be gained by submitting those intended for the barrels of guns to consolidation under the hammer. This process would in a great degree relieve the mass from the strains of elongation and compression which in every description of casting is present in passing from the fluid to the solid state.

In the manufacture of ordnance, whether composed of steel or cast iron, it is desirable that the laws of cooling and crystallization should be carefully observed, in order to equalize the contraction and render the casting as free from strain, and as uniform as possible in its molecular formation.

Digitized by Google

## CHAPTER IX.

### ON THE PROPERTIES OF IRON ARMOUR-PLATES, AND THEIR RESISTANCE TO SHOT AT HIGH VELOCITIES.

1. The best mode of employing armour-plates for the protection of the sides of ships is a problem yet to be solved, and although we have had several practical examples of their powers of resistance, as exhibited in the ironclads, monitors, &c., of the American navy in actual service, the results are far from satisfactory as regards the question of attack and defence. During experiments of nearly four years' duration, at Shoeburyness, the improvement in the manufacture of guns has outweighed that of the plates; and although plates can be made that will resist shot from the largest guns ever yet constructed, they are, nevertheless, of no practical value in the shape of armour-clad vessels against large guns, as we are limited in weight to the carrying powers of the ship. This being the case, it becomes a question of the deepest importance to devise a description of armour that a ship can carry, and which is at the same time capable of resisting the immensely heavy and powerful ordnance now being constructed.

2. The recent bombardment of Fort Fisher by the Federal ironclads and monitors throws some light on the subject, and the report of Admiral Porter on the question of armour-plated vessels is not without value. It must, however, be borne in mind, that the guns in the fort were, neither for weight nor number, a match for those in the fleet; and having to sustain an attack from vessels that poured in a storm of shot and shell for three successive days, the latter alone amounting to 25,000, it is not surprising that so little damage was inflicted upon the vessels engaged in the bombardment.

Admiral Porter in his report states that 'his late experiment with the monitor-class of vessels, under fire at sea and in

Digitized by Google

riding out heavy gales, justifies him in making a special report in relation to a class of vessels about which there has been great difference of opinion.' He instances the monitors 'Manadnook,' 'Sangus,' 'Mahopac,' and 'Canonicus,' as attacking the batteries at Howlett, on the James River. At that point the Confederates had a 200-pounder rifled gun mounted, one of the shot or shell from which struck the 'Sangus' fair on the turret, and knocked out or loosened 40 bolts. This, the Admiral observed, 'was owing to their being driven from inside to outside, instead of from outside to in.' The turret was not, however, materially injured, as, having been repaired in about two weeks, she was again in active service.

As seagoing vessels they were reported to have answered every purpose for which they were constructed, but in rough weather the sea swept over the turrets and down the funnels, to the great discomfort of the officers and crew; the complaint from their commanders, when signalled, being that '*they were quite well, only a little damp.*' All these vessels, according to the Admiral's account, rode out a severe gale in the Atlantic without accident; some of the smaller monitors, the 'Mahopac' and 'Canonicus,' almost disappearing in the trough of the sea.

It would appear that the 'Mahopac' is a strong well-built vessel, and, judging from the Admiral's statement, 'could destroy any vessel in the French or British navy, and lay their towns under contribution.' This and the other vessels have, we believe, been five days under fire from Fort Fisher, at a distance of 800 yards; and although thus exposed, within short range, they were seldom hit, and received no material injury.

Comparing the monitors or turret-vessels with the ironsides, their fire, according to Admiral Porter, is very 'slow, and not calculated to silence heavy batteries, which require a rapid and continuous fire to drive the men from the guns; but they are famous coadjutors in a fight—they can put in heavy blows, which tell on casemates and bombproofs.'

From the above it would appear that the Admiral who commanded the Federal fleet at Wilmington is not altogether satisfied with either monitors or ironsides. He seems to prefer the latter and heavy frigates, as being most effective against plated vessels, bombproofs, and brick and stone walls. He

Digitized by Google

evidently leans to the ironsides, by stating 'that he had never seen a vessel that came up to his idea of what is required for effective operations, as the ironclads, which unite many good qualities, would be no match for the "Manadnook". in a fight, the latter having more speed.' This opinion evidently shows that speed and heavy guns are two essential elements of success.

3. The naval engineers of this country are probably best able to estimate to what extent the American admiral is entitled to credit in his estimation of the powers of the British navy. With the speed of our ships, and the weight of metal they are calculated to carry, he is evidently not conversant; but we should not be justified in treating with disrespect the opinions of an officer whose experience with this class of vessels in actual service is greater than that of any of our commanders, who must necessarily be comparatively unacquainted with this new system of warfare, and the handling of vessels of this description under fire from an enemy's forts. On this question it is, therefore, important to have the views of such men as Admiral Porter freely and honestly expressed, as, in the present state of divided opinion, the comparative values of the turret and broadside principle can only be determined by the powers of attack and defence which they respectively exhibit under fire. It would appear that the turret principle is defective as regards the capacity of armament which that principle furnishes, as, according to accounts, the monitors are only about 1,000 tons burden, and must be limited for space in working heavy guns in the interior of the turrets. The ironclad and broadside principle is free from these defects, although it must be admitted that the power of revolving the turrets and directing the guns is of some importance. On the whole, it would seem that the Admiral prefers the broadside principle, as also the ironsides, for offensive operations, the monitors being much slower and less accurate in their fire, and therefore less adapted for silencing heavy batteries. These statements enable us to draw a comparison between the American navy and our own, and, judging from what has been done, the author has no hesitation in affirming that we are in armour, tonnage, and weight of metal, in advance of the American navy.

Digitized by Google

4. It has been stated that the labours of the Iron Plate Committee led to results of considerable importance in regard to the composition and character of the iron used in the manufacture of armour-plates. The first experiments indicated numerous defects in the manufacture, such as imperfect welding, hardness and brittleness in the material, and a great want of homogeneity and uniformity in the mass, so that the fracture produced by a heavy blow presented a crystalline structure more allied to that of cast than to that of wrought iron.

These defects were so apparent, that a shot passing through the plate broke it up in large masses, leaving cracks and fissures radiating from the centre of perforation in a star-like form, similar to what is shown in the annexed drawing (fig. 60). This was not, however, the only objection, as the laminated character of the plate and the imperfect welding caused the different layers to separate and tear asunder in the shape of bark torn from trees, as shown in fig. 61: and these defects, taken in connection with the brittle state of the plates, and the numerous cracks (which extended from two to three feet)

Fig. 60.

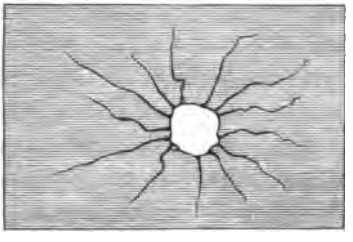


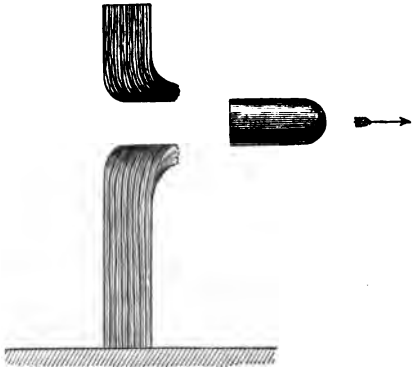
Fig. 61.

Digitized by Google

radiating from the centre in every direction, rendered the plate exceedingly insecure if struck a second time by a shot. In this latter case large flat pieces were in actual practice forced out, leaving an immense gap in the side of the ship.

By repeated trials, great care being taken in selecting the materials, the manufacturers, acting under the direction of the Iron Plate Committee, have at length overcome all difficulties, and have succeeded in producing a perfectly solid ductile plate, similar to that shown in section at fig. 62, which, it will be noticed, exhibits a much more ductile structure than that shown in fig. 61.

Fig. 62.



5. It might be desirable to compare the American armour-plates, as regards their quality and their power of resistance to shot, with our own manufacture. Unfortunately, however, we are not in possession of sufficient data to make this comparison, as the introduction of armour-plated ships is as new to the Americans as it is to the nations of Europe. This is evidently the case, as both Federals and Confederates have resorted to various shifts to protect their vessels, and give to them, by the introduction of chains, railway bars and plates, the semblance without the security which a well-constructed iron-plated ship would effect. In fact, it is questionable whether the Americans have yet arrived at the same state of perfection in the construction of their ironclads as that which has been attained in this country and in France. Undoubtedly the war now raging in that country* must have stimulated the inventive faculties of the people, and led to some improvements in the construction of armour-ships; and there is probably no people in the world more ready at contrivances to meet urgent requirements than the people of the American States.

* Since the above was written the Southern States have sustained a crushing defeat, and peace has again been restored to the Union.

Digitized by Google

6. Having shown, as far as our knowledge extends, what progress has been made in the American navy for protecting their ships against projectiles, it may be interesting to explain what has been done by the Government of this country and by that of France. Most of the French ironclads are of wood, and from a series of armour-plates sent over to this country it has been ascertained that the iron is about the same in quality but not so well manufactured as that employed for similar purposes by the Admiralty. The following summaries of results of experimental tests, applied to the French as well as the English armour-plates, are taken from the Report of the Iron Plate Committee.

It will be seen from Table I. that Messrs. J. Brown & Co.'s plates give the greatest tensile resistance, and Messrs. Beale & Co.'s and Messrs. Cammell & Co.'s plates the least. All the others are of fair average strength, excepting the unannealed plate, which exhibits greatly increased powers of elongation, as compared with the other irons, as well as with the annealed specimen from the same plate. As respects compression, there is a remarkable uniformity in the whole of the specimens, the same weight of 91·5 tons producing as nearly as possible the same effect.

TABLE I.—GENERAL SUMMARY OF DIFFERENT PLATES EXPERIMENTED ON.

| Description of Armour Plate | Tension | | Work done in Foot Pounds | Compression | |
|---|---|---|---|---|---|
| | Mean Breaking Weight per Square Inch in Tons | Mean Ultimate Elongation per Unit of Length | | Mean Weight per Square Inch of original Area in Tons | Mean Compression per Unit of Length |
| Mean of 3-inch Plate (First Report, pp. 12, 13, 14) . . . | 25·031 | ·2689 | 7,787 | 90·967 | ·502 |
| Mean of French Plates (Third Report) . . | 22·344 | ·2188 | 5,476 | 91·550 | ·556 |
| Mean of Millwall Plates (Third Report) . . | 21·840 | ·1770 | 4,331 | 91·550 | ·558 |
| Messrs. Brown's Armour Plate (Third Report) . | 25·297 | ·1472 | 4,170 | 73·438 | ·470 |
| Unannealed Armour Plate (Third Report) . | 23·205 | ·4000 | 10,396 | 91·550 | ·512 |
| Annealed Armour Plate (Third Report) . . | 21·901 | ·2100 | 5,151 | 91·550 | ·535 |
| Messrs. Beale and Co.'s Armour Plate . . | 17·699 | ·0781 | 1,548 | 91·550 | ·552 |
| Mean of Messrs. Cammell and Co.'s Armour Plates . . . | 18·384 | ·1042 | 2,145 | 91·550 | ·603 |
| Mean of all Experiments | 21·962 | ·2005 | 5,125 | 89·213 | ·536 |

Digitized by Google

In the summary of experiments on indentation contained in Table II. the differences are inconsiderable, with the exception of the Millwall and unannealed plates, which in both experiments exhibit greatly increased powers of resistance, the depths when penetrated by the flat-ended punch being in the ratio of nearly 1 : 2, or about one-half the depth as compared with most of the other irons. With the round-ended punch the depths approximate much closer, being about one-third less than the softer irons.

TABLE II.—GENERAL SUMMARY OF INDENTATION.

| Description of Armour Plate | Pressure on Punch | | Mean Indentation in Inches | Remarks |
|---|---|---|---|---|
| | lbs. | tons | | |
| Mean of French Plates, Third Report | 99·540 | 44·437 | ·138 | Flat-ended punch |
| Mean of Millwall Plates, Third Report | | | ·064 | |
| Unannealed Plate, Third Report | | | ·055 | |
| Annealed Plate | | | ·096 | |
| Messrs. Beale and Co.'s Plate | | | ·101 | |
| Messrs. Cammel and Co.'s Plates | | | ·140 | |
| Mean of all the Experiments | 99,540 | 44·437 | ·099 | |
| Mean of French Plates, Third Report | 99,540 | 44·437 | ·336 | Round-ended punch |
| Mean of Millwall Plates, Third Report | | | ·251 | |
| Unannealed Plate, Third Report | | | ·209 | |
| Annealed Plate | | | ·236 | |
| Messrs. Beale and Co.'s Plate | | | ·297 | |
| Mean of Messrs. Cammell and Co.'s Plates | | | ·300 | |
| Mean of all the Experiments | 99,540 | 44·437 | ·271 | |

The ultimate resistances of the different plates to rupture, as shown in Table III., do not differ widely from the average resistance.

These resistances, with the exception of the 3-inch-plates, may be fairly taken at 34 tons for the flat-ended punch, and 38 tons for the round-ended one—or, in round numbers, at 40 tons per square inch.

Digitized by Google

TABLE III.—GENERAL SUMMARY OF PUNCHING.

| Description of Armour Plate (Specimens ¾ inch thick) | Pressure on Punch at Rupture | | Mean Indentation in Inches | Remarks |
|---|---|---|---|---|
| | lbs. | tons | | |
| Mean of 3-inch Plates . . | 83,484 | 37·269 | ·249 | Flat-ended punch |
| Mean of French Plates . . | 75,220 | 33·580 | ·237 | |
| Mean of Millwall Plates . . | 79,828 | 35·637 | ·165 | |
| Unannealed Plate . . . | 78,036 | 34·837 | ·190 | |
| Annealed Plate . . . | 70,868 | 31·637 | ·230 | |
| Messrs. Beale and Co.'s Plate . | 76,244 | 34·037 | ·180 | |
| Mean of Messrs. Cammell and Co.'s Plates . . . | 72,660 | 32·437 | ·147 | |
| Mean of all the Experiments | 76,620 | 34·205 | ·1997 | |
| Mean of 3-inch Plates . . | 98,495 | 43·968 | ·443 | Round-ended punch |
| Mean of French Plates . . | 85,972 | 38·379 | ·489 | |
| Mean of Millwall Plates . . | 91,476 | 40·837 | ·439 | |
| Unannealed Plate . . . | 88,788 | 39·637 | ·456 | |
| Annealed Plate . . . | 83,412 | 37·237 | ·454 | |
| Messrs. Beale and Co.'s Plate . | 85,204 | 38·037 | ·472 | |
| Mean of Messrs. Cammell and Co.'s Plates . . . | 79,828 | 35·637 | ·427 | |
| Mean of all the Experiments | 87,596 | 39·105 | ·454 | |

Taking the foregoing summary of results as a whole, it may be inferred that the two classes of plates manufactured by Messrs. Beale and Cammell are nearly the same in their powers of resistance to tension, but inferior to those from other manufacturers that have been experimented upon under precisely the same circumstances. As respects compression, indentation, and punching, they do not vary to any great extent with the softer description of irons; and their powers to resist impact may be considered nearly equal to the more ductile irons, which exhibit greater tenacity when torn asunder by a tensile strain. They would, however, be inferior in their resistance to shot calculated to perforate armour-plates, as the harder description of iron is subject to fracture, breaks up more readily into splinters from impact, and in through-shots they are more widely and destructively dispersed. It is therefore a desideratum in the manufacture of armour-plates that ductility and tenacity should enter largely into the composition; and, moreover, clean slabs and sound welding are considerations of vital importance in the manufacture and consolidation of a tenacious and powerfully-resisting armour-plate.

Digitized by Google

In closing these researches into the strengths and other properties of manufactured armour-plates, we venture to hope that the experiments may be useful in directing attention to the elementary conditions necessary to be observed in the different stages of manufacture, and we trust they may ultimately lead to the production of sound and perfect armour-plates. These conditions have been derived from direct experiment, first by statical pressure, and subsequently by the impact of shot calculated to produce the greatest possible amount of damage on ships and forts covered with iron envelopes similar in form to those so often exhibited in the targets at Shoeburyness.

7. To show the nature of the experiments carried on at Shoeburyness by the Iron Plate Committee, we have selected those made with one of the latest targets, that of the 'Lord Warden,' which, in its powers of resistance, will admit of comparison with the armour-plates of the 'Warrior' and others.

The target, 20 feet by 9 feet, was constructed by the Lords Commissioners of the Admiralty, to represent the ordinary construction of a wooden ship armour-plated, with the addition of a thick iron skin worked outside of the frame-timbers of the ship.

The following are the scantlings:—Frame-timbers moulded, 12½ inches;* iron diagonal riders connecting the frame-timbers, 6 inches by 1¼ inch; inner planking, 8 inches thick; iron skin, 1½ inch thick; outside planking, 8½ inches thick; rolled armour-plates, 20 feet by 4 feet 6 inches by 4·5 inches, manufactured by the Millwall Company.

Armour-plate bolts, 2½ inches diameter. Iron washers were placed under the bolt-heads and rested on india-rubber washers, the latter being let into the timber:—

| | ins. | ins. |
|---|---|---|
| Deck beams, lower | 15 | by 12 |
| „ upper | 16 | „ 16 |
| Waterway, lower | 15 | „ 15 |
| „ upper | 13 | „ 14 |
| Deck planking, lower | 4 | |
| „ upper | 4 | |

Iron knees to each beam—weight 3 cwt. 2 qrs. 21 lbs.
The total weight of the target—38 tons 16 cwt. 0 qrs. 13 lbs.
Range 200 yards.

* Occasional, spaced several feet apart, and inclined at about an angle of 45°.



Digitized by Google

The guns used in this experiment were as follows:—

| | | Weight tons | cwts. | qrs. | lbs. |
|---|---|---|---|---|---|
| One | 68-pounder smooth-bore muzzle-loading gun . | 4 | 15 | 0 | 0 |
| One | 9·22″ muzzle-loading rifle gun, 11′ long 6 grooves | 6 | 11 | 2 | 11 |
| One | 9·22″ „ „ 13′. 3″ „ 6 „ | 12 | 2 | 2 | 0 |
| One | 10·5″ „ „ 11′. 7″ „ 10 „ | 11 | 15 | 2 | 0 |
| One | 7″ „ „ 10′. 9″ „ 6 „ | 6 | 13 | 3 | 0 |

The following shot and shell struck the target:—

From 10·5″ Armstrong rifled gun . . } Spherical steel shot; one, weight, 168·25 lbs. Cylindrical steel shot; one, weight, 301 lbs.

From 9·22″ rifled 12-ton gun . . . } Cylindrical steel shot; four, total weight, 885·5 lbs.

From 9·22″ rifled 6½-ton gun . . . { Spherical steel shot; one, weight, 144·25 lbs. Spherical cast iron shot; two, weight, 208·75 lbs. Cylindrical steel shell; two, weight, 349·5 lbs.

From 7·0″ muzzle-loading rifled gun } Cylindrical steel shot; one; weight, 100 lbs.

From 68-pounder smooth-bore gun . } Solid steel shot; one; weight, 71·5 lbs.

TABLE IV.—NATURE OF ORDNANCE, WEIGHT OF SHOT, &C., FIRED AGAINST THE 'LORD WARDEN' TARGET.

| Number of Round | Nature of Ordnance | Projectile | | | Charge of Powder in lbs. | Depth of Indentation in Inches | Velocity at 510′ |
|---|---|---|---|---|---|---|---|
| | | Nature | Weight in Pounds | Form and Diameter | | | |
| | | | | inches | | | |
| 1 | 68-pounder smooth-bore gun | Steel solid shot | 71·4 | Spherical 7·94 | 16 | 3·6 | Not observed |
| 2 | 9·22″ rifled 6½-ton gun | Steel solid shot | 114·2 | Spherical 9·14 | 25 | .. | 1444·0 |
| 3 | 9·22″ rifled 6½-ton gun | Steel shell . | 174·5* | Cylindrical 9·14 | 20 | .. | 1006·6 |
| 4 | 7″ muzzle-loading rifled gun | Steel solid shot | 100 | Cylindrical 6·91 | 25 | .. | 1507·2 |
| 5 | 10·5″ Armstrong rifled gun | Steel solid shot | 168·25 | Spherical 10·43 | 50 | .. | 1593·8 |
| 6 | 9·22″ 12-ton rifled gun | Steel solid shot | 221 | Cylindrical 9·14 | 44 | .. | 1461·1 |
| 7 | 9·22″ 6½-ton gun . | Capt. Palliser's chilled cast-iron shot | 103·75 | Spherical 9·17 | 25 | 6·8 | 1532·0 |
| 8 | 9·22″ 12-ton gun . | Steel shot. . | 221 | Cylindrical 9·14 | 30 | .. | Missed wires |
| 9 | 10·5″ rifled gun . | Steel solid shot | 301·0 | Cylindrical 10·46 | 45 | Through | 1254·5. |
| 10 | 9·22″ 12-ton rifled gun | Steel solid shot | 221·5 | Cylindrical 9·14 | 30 | Through | 1292·6 |
| 11 | 9·22″ 6½-ton rifled gun | Steel shell . | 175* | Cylindrical 9·14 | 20 | Through | 1146·6 |
| 12 | 9·22″ 12-ton rifled gun | Steel solid shot | 222 | Cylindrical 9·14 | 30 | Through | 1351·5 |
| 13 | 9·22″ 6½-ton rifled gun | Capt. Palliser's chilled cast-iron shot | 105·437 | Spherical 9·18 | 25 | .. | 1448·3 |

* Empty.

Digitized by Google

The first round was a cast-steel shot of 71 lbs. weight, fired from a 68-pounder smooth-bore gun, with the service-charge of 16 lbs. The total depth of penetration was 4·1 inches. The shot was broken in half; but the result obtained is satisfactory, considering that it was only cast metal (not forged), and therefore of a cheap nature. The striking velocity was about 1,410 feet per second, and the work amounted to 1,988,100 foot-pounds.

No. 2 round was a spherical steel shot weighing 114 lbs., fired from a 9·22-inch rifled 6½-ton gun, with a charge of 25 lbs. It penetrated the armour-plate and about 12 inches into wood backing; broke one 'waterway,' and started inner planking. Shot remained in hole and appeared to be a good deal 'set up.' This shot struck with a velocity of 1,444 feet, and carried 3,703,007 foot-pounds of 'work.'

No. 3 round was a steel shell weighing 182½ lbs. (including a bursting charge of 7½ lbs.), fired from the 9·22-inch gun with a charge of 20 lbs. It penetrated to a depth of 6·5 inches, and made a hole in the plate 12½ inches diameter. The shelf-piece at the back was started, and the inner planking was rent over a space of 4 feet by 2 feet. The shell split in half, and was picked up in front of the target; it had a striking velocity of 1,006 feet.

Round No. 4 was a steel cylindrical solid shot of 100 lbs. weight, fired with a charge of 25 lbs. from a 7-inch rifled gun. It struck near the top of the target and penetrated to the iron skin, which was indented to a depth of 3½ inches. The striking velocity was 1,507 feet, and the work was 3,530,127 foot-pounds. This shot struck too high to give any satisfactory result.

Round No. 5 was a steel spherical solid shot weighing 168 lbs., fired from a 10·5-inch rifled gun with a 50-lb. charge. It penetrated to a depth of 12 inches plus its own diameter, making a hole of 11 inches in the armour-plate. A shelf-piece was driven half through, one iron knee was cracked across at bend, and interior planking was splintered and damaged over an area of 6 feet by 3 feet. The striking velocity of this shot was 1,593 feet, and the work carried amounted to 6,645,010 foot-pounds.

Round No. 6 was a steel cylindrical solid shot weighing 221 lbs., fired from a 9·22-inch 12½-ton rifled gun with a 44-lb.



Digitized by Google

charge. It penetrated the target, making a hole 11 inches diameter in the plate. The aperture at the back measured about 8 inches, and the inner plating was splintered over a space of 18 inches by 18 inches; one rivet was broken, and an iron knee was started. The striking velocity of the shot was 1,461 feet, and the work 7,332,577 foot-pounds.

Round No. 7 was a spherical iron shot cast in chill, weighing 103 lbs., and fired from a 9·22-inch rifled gun with a 25-lb. charge. It penetrated to a depth of 6·8 inches, and broke up; only slight damage was caused to the inside of the target. The striking velocity was 1,532 feet, and the work 3,785,084 foot-pounds.

Round No. 8 was a steel cylindrical solid shot weighing 221 lbs., fired from a 9·22-inch rifled gun with a reduced charge of 30 lbs. It grazed the sloping plate at the foot of the target, and then struck the bottom of the lower plate, breaking away 15 inches by 9 inches of the plate. The velocity was not obtained.

Round No. 9 was a steel cylindrical solid shot weighing 301 lbs., fired from a 10·5-inch rifled gun with a 45-lb. charge. It penetrated the target, broke one piece of iron knee 4 feet long, and drove it 16 yards to the rear; five or six backing bolts broken; inner planking damaged for a space of 8 feet by 4 feet; large splinters of wood were broken off and scattered about. The velocity of the shot was 1,254 feet, and the work in it amounted to 7,356,901 foot-pounds.

Round No. 10 was a repetition of Round 8, viz., a steel cylindrical shot fired from a 9·22-inch gun with a reduced charge. It struck at the edge of an old shot-hole and penetrated the target; the inner planking was driven out and destroyed over a space of 3 feet 9 inches by 2 feet 3 inches; the splinters of wood and skin were driven 20 yards beyond the target. The striking velocity was 1,292 feet, and the work in the shot amounted to 5,756,016 foot-pounds.

Round No. 11 was a steel shot 180 lbs. weight (including bursting charge of 7½ lbs.), fired from a 9·22-inch rifled gun, with a charge of 20 lbs. It struck just below the hole made by the fifth round, penetrated the target, exploded inside, and ignited the timber backing: 6 feet by 3 feet 6 inches of inner

Digitized by Google

planking (weakened by fifth round) was blown out. The shell did not break up. The striking velocity was 1,146 feet. The fire was easily extinguished.

Round No. 12 was a repetition of Rounds 8 and 10. It struck at the edge of two old shot-holes, made by the sixth and tenth rounds, and penetrated; but it was a very weak part of the target, the inner planking having been destroyed by previous rounds. The striking velocity was 1,351 feet, and the work in the shot was 6,307,330 foot-pounds.

The last round was an iron spherical shot, cast in chill, weighing 105 lbs. It penetrated to a depth of 10 inches and broke up; the striking velocity of the shot was 1,448 feet.

From the above statement it will be seen that the relative damaging powers of the guns are in order as follows:—

10·5″ gun with cylindrical shot and 45 lbs. charge.
9·22″ (12½-ton gun) cylindrical shot and 44 lbs. charge.
10·5″ gun with spherical shot and 50 lbs. charge.
9·22″ (6½-ton gun) spherical shot and 25 lbs. charge.
7·0″ gun with cylindrical shot and 25 lbs. charge.

This agrees with the amount of 'work' accumulated in the shot, viz.:—

| | | |
|---|---|---|
| 10·5″ gun with cylindrical shot . . . | 7,356,901 | foot pounds |
| 9·22″ (12½-ton gun) with cylindrical shot | 7,332,577 | ,, |
| 10·5″ gun with spherical shot . . . | 6,645,010 | ,, |
| 9·22″ (6½-ton gun) with spherical shot . | 3,703,007 | ,, |
| 7·0″ gun . . . . . | 3,530,127 | ,, |

The 10·5-inch rifled gun with a spherical steel shot, weighing 168 lbs., and fired with a 50-lb. charge, did less work on the target than the 9·22-inch rifled gun, fired with an elongated steel shot of 221 lbs. and a charge of 44 lbs., which is due to the superiority of the latter in regard to the amount of work lost by the change of form which the shot undergoes; and in the opinion of the Committee, this superiority is mainly due to the fact that the elongated shot, as compared with the spherical shot of the same weight, has the advantage of being better adapted for the process of tempering.

The cast-iron chilled shot did considerable damage to the armour-plates, and although the material is inferior to steel for this purpose, yet it appeared to the Committee deserving of

Digitized by Google

further trial, as very good results were obtained from it in all the experiments made, and the cost very little more than that of the cast-iron shot of the service.

The experiment on the 'Lord Warden' target was the first conducted by the Committee with a view of testing the resisting power of a wooden ship armour-plated. The results of the experiment would seem to show that the large quantity of iron entering into this construction is not disposed of in the most advantageous manner.

The weight per square foot of the target is in excess of the 'Warrior' and the 'Bellerophon,' as will be seen from the following statement:—

| | |
|---|---|
| 'Lord Warden' . . . . | 482·9 lbs. per square foot. |
| 'Warrior' . . . . . | 341 „ „ |
| 'Bellerophon' . . . . | 393·2 „ „ |

The 'Chalmers' target—which, though of much smaller area, can only be considered under the most unfavourable calculation as of about the same weight as the 'Lord Warden' target—suffered much less from the blow of 10·5-inch steel projectiles with 45-lb. charges; the area of destruction in the 'Lord Warden' target was 8 feet by 4 feet, whereas the area of destruction in the 'Chalmers' target was 2 feet by 1½ feet.

The number of splinters of wood in the rear of the 'Lord Warden' target (amounting to 150, of weights varying from 2 lbs. to 14 lbs.) are much greater than ever before occurred in a target representing an iron ship, thus rendering it evident that the internal iron skin is an advantage. This might probably be obtained in some degree also in wooden ships by means of an iron lining of plates calculated to prevent the dispersion of splinters.

The wrought-iron knees broke in several places. All iron-work of this sort exposed to the jar of shot ought to be of the best and toughest material, and well rounded at the angles.

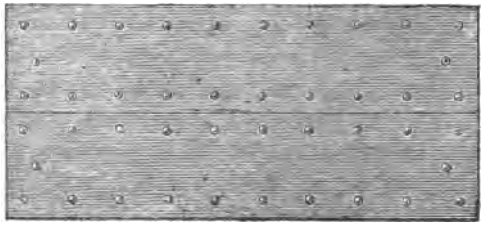
The armour-plate bolts stood remarkably well, not a single one having been broken at the bolt-head. No doubt the great mass of timber through which they passed, together with the elastic washers, assisted much in relieving the strain on the bolt-heads.

Digitized by Google

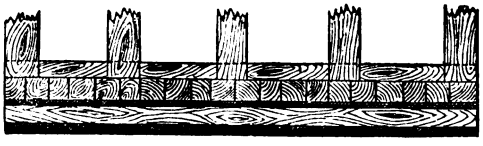
The armour-plates which were made at the Millwall Works were of good material, being free from radiating cracks after the very severe trial to which they were subjected; but were badly welded, the layers of which they were composed separating freely in many places from each other.

The following drawing (fig. 63) represents the form, dimensions, and thickness of plates, &c. of the 'Lord Warden' target:—

Fig. 63.



Bolts two inches diameter.



Comparing the foregoing experiments on the 'Lord Warden' target, it is obvious, notwithstanding the great thickness of the timber employed in the construction, that the timber-built armour-plated vessel is much more insecure than one built of iron, not only as regards the danger from fire and the explosion of shells, but the injury arising from splinters is so much greater in wood than in iron that it becomes almost imperative to have an interior skin of the latter material in order to catch the splinters and prevent their dispersion between-decks.

8. The numerous experiments made on targets at Portsmouth and Shoeburyness have elicited almost everything that can be said on the subject of guns and iron armour-plates. It is, however, evident that we have all along laboured under a mistake in regard to the weight and power of rifled ordnance. We have been in the habit of calling a gun with a cylindrical bolt weighing 100 lbs. a hundred-pounder, whereas the actual

Digitized by Google

power of such a gun—according to the old standard—is the weight of a spherical shot that can be discharged from that gun. This appears to be the true measure of its power, if it is to be compared with those on the old smooth-bore principle; and hence it follows that the 68-pounder smooth-bore was more than a match, in its destructive effects, to the so-called rifled 110-pounder gun. We have always deprecated this assumption of rating rifled ordnance by the weight of the projectile; and this system of overrating the power of guns leads not only to error, but it gives an undue preponderance to weapons that are essentially defective, and that cannot be trusted in actual service.

Doubtless, much will depend on the magnitude of the charge of powder, if rendered equivalent to the weight of the projectile; but this cannot be done with safety in a built-up rifled gun, unless made proportionably stronger, to meet the augmented pressure on the chamber of the gun. These are considerations which appear to require attention, as the destructive power of a gun depends on the quantity of powder consumed, and in rifled guns with long bolts and small bore this useful and effective consumption of powder is not easily accomplished.

It has been demonstrated that the resistance of iron plates to shot is directly as the squares of the thickness. Our statical experiments on punching prove this fact; and assuming that the same law of resistance is true to the force of impact from shot, it thence follows that a small-bore gun with a heavy charge of powder is more effective as a perforator than the enormously large ordnance such as the 600-pounder to which we have referred. In the former case, say the 7-inch bore with a steel cylindrical shot of 100 lbs. weight, fired with a charge of 25 lbs. of powder and a striking velocity of 1,507 feet per second, penetrated a 4½-inch thick plate, cutting a hole 22 inches in circumference; whilst the 600-pounder, with a cylindrical shot six times the weight and a charge of 100 lbs. of powder, cutting a similar hole 41·8 inches (nearly double the circumference), would not perforate a plate double the thickness, as the area of the bore of the large gun (13·3 inches in diameter) being nearly four times that of the 7-inch gun, would require four times the pressure per inch of surface to produce the same proportionate result. If this be correct, it is obvious that

Digitized by Google

our very large guns must be made much heavier and stronger than any yet contemplated or ever likely to be constructed. Reasoning from these facts, it would appear that the effect of steel shot upon armour-plates depends almost entirely on the quantity of powder usefully consumed in the charge, and the resisting powers of the gun: and assuming this to be true, we may therefore reasonably conclude that if vessels are armour-plated from 3 to 4 feet above and from 4 to 5 feet below the water-line—dispensing with all further protection—they will be able to carry plates of from 8 to 9 inches in thickness, and may therefore set at defiance the largest and most powerful guns yet made, or that which in ordinary circumstances can be safely constructed.*

9. The following chapter being intimately connected with the subject of the present inquiry, it will not be necessary to pursue the subject here more in detail. We may therefore, for any further remarks we have to offer on the resistance of armour-plates to projectiles at high velocities, refer the reader to Chapter X., in which he will find rules and examples whereby plates can be proportioned so as to resist shot of any form composed of cast iron, wrought iron, or steel; and, moreover, the student will be enabled to form an opinion of the nature of the analytical and synthetical processes by which we have deduced practical formulæ from actual experiment.

* Shortly after these remarks were made, a new target was constructed, representing the side of the 'Hercules,' 4 feet 2½ inches thick, and of this 11½ inches was iron, the remainder being made up of oak or teak. The weight of this target was 520 pounds per square foot, which is greatly in excess of the 'Warrior,' being in the ratio of 520 : 347.

On this thickness of plates and backing the 300-pounder guns made no serious impression, and it is questionable, even according to Sir William Armstrong's showing, whether his 600-pounder, with a full charge of 70 or even 90 pounds of powder, would have made a clear passage through that target.

Digitized by Google

## CHAPTER X.

### ON THE IMPACT AND RESISTANCE OF SHOT AND SHELLS FIRED AGAINST ARMOUR-PLATES.

1. In these inquiries we have not only to determine the best means of defence, but also the most effective system of attack. After having ascertained what is the best description of armour-plates for resisting the destructive force of projectiles generally, it is equally important that we should know what is the kind of shot best calculated to perforate or to rupture those plates. To employ cast iron, which is broken to pieces by the force of its own momentum when striking an armour-plate, is to lose one-half of its penetrative powers. On the other hand, to use wrought iron, which, owing to its plastic nature, is distorted and flattened by a comparatively moderate blow, is, to say the least of it, a very improper and very unsatisfactory instrument of attack. If we are to cover our ships with powerfully-resisting armour-plates, projectiles of greatly increased tenacity must be employed to penetrate them; and, moreover, they must be of that class calculated to retain their original form, and able to perforate and damage to the greatest extent every object that stands in the way of their flight.

2. It is an error to attribute too much to the form, without considering the nature of the material of which projectiles are composed, and the nature of the work they have to perform. A shot is the vehicle for transferring mechanical force from the gun to the object of attack, and this again becomes the recipient of the work done by the force of the blow.

3. The work accumulated in a shot discharged from a cannon is measured by the weight of the shot multiplied by the square of the velocity, and is expressed by the formula—

$$U = \frac{w\, v^2}{2\, g} \quad \ldots (1)$$

Digitized by Google

where $w$ is put for the weight of the shot in lbs., $v$ is its velocity in feet per second, and $g$ equals $32\frac{1}{6}$, the velocity acquired per second by a body falling freely by the force of gravity.

Thus, if we take a 6-lb. shot moving at the rate of 1,200 feet per second, the work accumulated in it

$$= \frac{6 \times (1200)^2}{2 \times 32\frac{1}{6}} = 134{,}400 \text{ foot-pounds.}$$

Similarly, the units of work accumulated or stored up in a 100-lb. shot moving with the same velocity

$$= 2{,}240{,}000 \text{ foot-pounds.}$$

That is to say, this comparatively small body has stored in it a dynamical power capable of lifting a weight of 1,000 tons 1 foot high in opposition to the force of gravity. This enormous power of accumulated work is generated by the explosion of the powder in the gun, and, before the shot can come to a state of rest, this work must be yielded up, or expended in the form of some kind of mechanical effect.

4. When the shot is perfectly hard, the whole of the work stored in it will be expended in rupturing the plate upon which it impinges; but if the shot be ductile or brittle, then a portion of this work will be uselessly expended in altering the form of the shot, or in breaking it into fragments.

The work expended in changing the form of an elongated shot is approximately expressed by the formula—

$$U = \tfrac{1}{2} p l,$$

where $p$ is put for the maximum or ultimate pressure upon the plate, and $l$ for the longitudinal compression which takes place.

If, however, the shot instantaneously regains its original form after the collision, or if the compression which it undergoes be very small, as in the case of tough hard steel bolts, then practically this work may be neglected, as being small compared with the whole work expended in the destruction of the plate; but when the material is soft and inelastic, as in the case of wrought iron or lead, the shot undergoes a permanent change of form, and thus a considerable amount of work is uselessly expended; or if the material is hard and brittle, as in the case of cast-iron shot, a large portion of work is liable to be wasted in the breaking-up of the material. Mr. Pole, in his first report

Digitized by Google

to the Iron Plate Committee, stated, as the result of his observations and deductions, that 'the destructive force carried by the shot will be the same in *amount* whatever be the material of which, or the shape in which, it be made.' But the more recent experiments of Mr. Whitworth and Sir W. Armstrong have shown that shot made of steel, more carefully and efficiently tempered than heretofore, produce, under the same circumstances, a far more damaging effect upon the armour-plate than shot made of wrought iron or of cast iron. Sir W. Armstrong made a further series of interesting experiments on the heat developed in the various kinds of shot by the concussion; and by the aid of the dynamic theory of heat, he was enabled to give an approximate estimate of the work lost in distorting the form of the different kinds of shot.* He found that with hard-tempered steel shot, not more than one-tenth of the whole work stored in it was lost on the projectile; whilst with soft steel shot it was about twice as much, and with soft wrought-iron shot it was more than one-half of the whole work in the shot. These experiments seem to warrant the conclusion that, in firing at strong armour-plates with cast or wrought-iron shot, about one-half the effect is lost in distorting or in breaking up the shot itself; and further, that with steel shot of tough temper, nearly the whole of the work stored in it is expended upon the plate.

5. The weight and form of shot are certainly of less importance, as regards the destructive effect upon the iron-plate target, than the nature of the material of which they are composed. With the same amount of work accumulated in two projectiles differing in size and weight, the smaller shot, with the greater velocity, produces a deeper indentation, but more limited in area; whereas the larger and heavier shot, with a slower velocity, produces a more extended though a less indented fracture. It will, therefore, be observed, that the damage done by the latter may be equal to, if not greater than, that done by the former, though the indentation produced in the plate may not be so great: and it is necessary to observe, that the amount of perfora-

* Mr. Whitworth was the first to perforate armour plates with steel shot, and the author repeatedly urged the Iron Plate Committee to undertake a series of experiments on the amount of heat developed by the impact of shot on iron plates.

Digitized by Google

tion produced in the plate cannot always be taken as the measure of the damage done to it by a shot. The fact is, the damage done to a plate by the impact of shot may be viewed in two distinct aspects—viz., either as regards the extent of the injury, or as regards the depth of the indentation. It is requisite that we should make this distinction in order to explain the apparent incongruity of the two formulæ hereafter given on this subject.

6. The author's experiments on punching led to the following general laws relative to the resistance of iron plates to a force tending to rupture them:—

The diameter of the punch being constant, the pressure requisite to produce rupture varies, approximately, as the thickness of the plate.

When the thickness of the plate is constant, the pressure requisite to produce rupture varies, approximately, as the diameter of the punch.

And, generally, the pressure requisite to produce rupture varies as the thickness of the plate multiplied by the diameter of the punch; or, what amounts to the same thing, as the area of the shearing surface abraded in the process of punching; that is,

$$\text{P} \propto r\,t$$

where P is the ultimate pressure in lbs., $t$ the thickness of the plate in inches, and $r$ the radius of the end of the punch.

Now the work, U, expended in the penetration of a plate by a force varying as the depth of penetration, is expressed by the formula, $\text{U} = \frac{1}{2}\,\text{P} \times \frac{1}{12}\,t$

When the size of the penetrating body is constant or neglected, then $\text{P} \propto t$, and

$$\therefore \text{U} = \tfrac{1}{2}\,\text{P} \times \frac{1}{12}\,t = \text{C}\,t^2 \ldots (2)$$

where the work requisite to rupture a plate varies as the square of its thickness, C being a constant.

And when we assume, $\text{P} \propto r\,t$, then

$$\text{U} = \text{C}\,r\,t^2 \ldots (3)$$

where the work requisite to *perforate* the plate varies as the square of its thickness multiplied by the radius of the shot.

7. From a careful induction of the results of the experiments

Digitized by Google

on the effects of shot on armour-plates of the best quality, it may be presumed that a 2½-inch plate is capable of resisting, without undergoing destructive rupture, the blow of a shot, with the ordinary service-charge, from a 25-pounder rifled cannon, and that a 5-inch plate is similarly capable of resisting the shot of a 100-pounder, the velocity of the shot being estimated at about 1,200 feet per second, and the service-charge at about one-eighth the weight of the shot.

Now by formula (2) we get—

$$c = u \times \frac{1}{t^2} = \frac{100 \times v^2}{2g} \times \frac{1}{5^2} \text{ or } \frac{25 \times v^2}{2g} \times \frac{1}{2 \cdot 5^2}$$

$$= \frac{2 v^2}{g} = 90000 \text{ nearly}$$

$$\therefore u = c t^2 = 90000 t^2$$

$$\therefore t = \frac{1}{300} \sqrt{u} \ldots (4)$$

which gives, approximately, the thickness of the plate in inches, where the work accumulated in the shot is $u = \frac{w v^2}{2g}$ as given in formula (1).

If the velocity be constant, or $v = 1200$, then

$$t = \tfrac{1}{2} \sqrt{w} \ldots (5)$$

that is, when the velocity is 1,200 feet per second, the thickness of the plate is equal to one-half the square root of the weight of the shot.

In the present state of our knowledge these results can only be regarded as rough approximations.

8. In the following investigations it is assumed that the damaging effect of the shot upon the plate is measured by the amount of the perforation or indentation produced.

With tough hard-tempered steel shot the work lost on the shot itself is comparatively small; and, therefore, in this case we may regard the value of $u$ in formula (3) as equal to the whole work accumulated in the projectile: hence we get

$$c' r t^2 = \frac{w v^2}{2g} \text{ and}$$

$$\therefore t = \sqrt{\frac{w v^2}{c r}} \ldots (6)$$

where $c$ is a constant to be deduced from the experiments with ordnance.

Digitized by Google

This is a general formula for the penetration of wrought-iron plates by hard round-ended steel projectiles, from which, knowing the weight, diameter, and velocity of the shot, and the value of the constant c, involving the shearing stress, the maximum thickness of penetration, $t$, can be found, where the whole work accumulated in the shot is supposed to be delivered upon the plate.

Cast and wrought-iron service shot are far from fulfilling the conditions assumed in this formula; but as it may be presumed that the work lost in distorting or in breaking up such shot is, for each class of shot, a certain proportional part of the whole work accumulated in the shot, the formula here proposed may be assumed as applying to all kinds of projectiles—with this limitation, that the value of the constant c must be determined from the experiments made with each class of projectiles.

## APPLICATION OF GENERAL FORMULA TO THE EXPERIMENTS AT SHOEBURYNESS.

9. For this purpose it is necessary to know the maximum thickness of perforation, or that thickness of wrought iron which any given shot exactly penetrates, being brought to a state of rest at the opposite side of the plate. The Shoeburyness experiments give the thickness of plates perforated by each size of shot up to the limits at which the plates resisted impact. If the mean be taken of the greatest thickness perforated and the least thickness which resisted the shot in each case, this will give the nearest approximation to the maximum thickness of perforation which under the circumstances can be obtained.

Taking these means for each series of iron plates separately, and averaging the results, we get the following numbers :—

| Description of Gun | Maximum Thickness of Perforation in Inches |
|---|---|
| Armstrong 6-pounder | 1·286 |
| „ 12 „ | 1·803 |
| „ 25 „ | 2·350 |
| „ 40 „ | 2·820 |

Substituting these values of $t$ in the general equation (6), we get for the value of the constant c = 3,374,940 : hence,

$$(7)\quad t = \sqrt{\frac{w\,v^2}{3374940\,r}}$$

Digitized by Google

Recalculating from this equation the values of $t$, and placing them beside the results obtained at Shoeburyness, we have the following table:—

TABLE I.—COMPARISON OF GENERAL FORMULA WITH EXPERIMENTS.

| Description of Gun | Weight of Shot in lbs. | Charge of Powder in lbs. | Velocity in Feet per Second | Semi-diameter of Shot in Inches | Maximum Thickness of Perforation in Inches | | Error of Formula |
|---|---|---|---|---|---|---|---|
| | | | | | By Experiment | By Formula | |
| Armstrong 6-pounder | 6·25 | 0·75 | 1,141 | 1·22 | 1·286 | 1·406 | $+\frac{1}{11}$ |
| „ 12 „ | 11·56 | 1·50 | 1,155 | 1·46 | 1·803 | 1·769 | $-\frac{1}{58}$ |
| „ 25 „ | 24·81 | 3·13 | 1,169 | 1·84 | 2·350 | 2·337 | $-\frac{1}{180}$ |
| „ 40 „ | 40·00 | 5·00 | 1,166 | 2·34 | 2·820 | 2·663 | $-\frac{1}{18}$ |
| „ 100 „ | 110·00 | 14·00 | 1,175 | 3·45 | ... | 3·613 | |
| Smooth bore 68 „ | 66·25 | 16·00 | 1,557 | 3·96 | ... | 3·470 | |

Looking to the fact that the formula is merely provisional, and in some respects derived from imperfect data, the correspondence between the experimental and calculated results is sufficiently striking.

The formula applies only to cases in which the action of the shot is approximately similar to that of punching, and not to cases such as the 3-inch steel plate and the 6-inch iron plate, which broke by transverse fracture. The increase of rigidity resulting from increase of thickness, apart from any question of the ductility of the material, decreases the resistance of the thicker plates.

At present it does not appear possible to rationalise satisfactorily the constant $c = 3{,}374{,}940$. It indicates, however, that a large part of the work accumulated in the shot is wasted through the breaking up of the shot itself. Another circumstance affecting the shearing stress is the size of the fracture, which was always considerably larger than the shot itself.

A similar formula to that given above was deduced from experiments with the wall-piece, for steel shot. These appeared to demonstrate that steel shot had a far higher penetrative value than the ordinary cast-iron service shot.

Placing the two in juxtaposition we have,—

For cast-iron Armstrong shot, $t = \sqrt{\frac{w\,v^2}{3374940\,r}}$.

For flat-faced tempered steel shot, $t = \sqrt{\frac{w\,v^2}{1568260\,r}}$

Digitized by Google

where $t$ is the maximum thickness of penetration in inches for projectiles of $w$ lbs. weight and 2 $r$ inches diameter at a velocity of $v$ feet per second. On comparing these formulæ it will be seen that the steel shot will penetrate thicker plates than the cast-iron shot in the ratio of $\sqrt{2} : 1$ or as 1·4 : 1 nearly. This is remarkably confirmed by the results of Sir William Armstrong's experiments, given at page 172.

We have before us the results of the trials with the Whitworth guns, with steel projectiles, flat-ended, like those of the wall-piece, from which it appears desirable to examine how far the anticipation of a high penetrative power in such missiles is borne out by the facts.

Unfortunately, the experiments with the Whitworth gun are not complete enough to determine the maximum thickness of perforation. In every case the armour-plate was pierced by the steel shot, but we are not entitled to infer that a somewhat greater thickness would not also have been penetrated. This might have been the case or it might not, but until the point at which the shot is thrown back from the target without penetrating is ascertained, we are not at liberty to assume that the maximum thickness of perforation has been reached, and hence we are without the necessary data for deducing a constant.

We have therefore, for comparison, calculated the maximum thickness of perforation for the Whitworth projectiles, by means of the formula deduced from the experiments with the wall-piece, and in the following table we place these results side by side with the thicknesses actually penetrated in the Shoeburyness experiments :—

TABLE II.—COMPARISON OF RESULTS OF EXPERIMENTS WITH WHITWORTH'S STEEL PROJECTILES, WITH THE FORMULA DEDUCED FROM THE WALL-PIECE.

| Description of Gun | Weight of Shot in lbs. | Charge of Powder in lbs. | Velocity of Shot in Feet per Second | Semi-diameter of Shot in Inches | Maximum Thickness of Penetration by Formula in Inches | Thickness actually penetrated in Inches |
|---|---|---|---|---|---|---|
| Wall-piece . . . | 0·3438 | ... | 1,141 | 0·435 | 0·81 | 0·81 |
| Whitworth 12-pounder | 12·06 | 1·875 | 1,202*a* | 1·500 | 2·72 | 2·50 |
| „ 12 „ | 12·16 | 1·750 | 1,157*a* | 1·500 | 2·63 | 2·00 *b* |
| „ 70 „ | 68·50 | 12·000 | 1,276 | 2·750 | 5·09 | 4·00 *c* |
| „ 120 „ | 129·00 | 23·000 | 1,278 | 3·500 | 6·20 | 4·50 *d* |
| „ 120 „ | 130·00 | 25·000 | 1,268 | 3·500 | 6·17 | 4·50 *e* |



Digitized by Google

*Remarks on foregoing Table.*

*a* These velocities are calculated.

*b* The shell penetrated 12 inches of wood backing, and buried itself in a sand-bank behind.

*c* The shot penetrated 13 inches of wood backing, and indented and cracked a 2-inch plate in the rear.

*d* This shot penetrated 20 inches of wood backing, and fractured the iron skin.

*e* The shell burst whilst penetrating the wood backing.

The results here given are satisfactory, considering the limited number of experiments which have been made. It is probable that the resistance to projectiles is not exactly as the square of the thickness of the plates, but in a slightly less ratio. Looking at the results of the author's statical experiments on punching, the formula,*—

$$t = \left(\frac{w\,v^2}{c\,r}\right)^{\frac{1}{1\cdot74}}$$

is more in accordance with the experimental results; but the labour of using this formula would not, in the present state of our knowledge, compensate for its greater accuracy.

COMPARISON OF RESULTS OF EXPERIMENTS, &c.

10. In this inquiry it may be of some importance to compare the experiments on the 'Lord Warden' target with that of the 'Warrior,' and in order to illustrate the immense force a ship of war may have to encounter, we give a table of results, showing the weight of shot discharged and the quantity of work done in foot-pounds on each of these and other targets:—

* In the experiments made by the Special Committee on Iron there are few results susceptible of calculation which bear on the relative penetrative power of projectiles of different forms and of various materials.

The most important, because that derived from the widest induction, is this—that while the maximum thickness of penetration given by the author's formula for cast-iron round-ended projectiles of the size and weight of the shot of the wall-piece is only 0·3 inch, the actual penetration of the *steel* flat-faced projectile was 0·8 inch, or 2·7 times as much. The difference is no doubt due, first, to the greater penetrative power of a flat-ended compared with a round-ended projectile; and, secondly, to the loss of work with cast iron, through the breaking-up of the shot.

From this and experiments on the 'Warrior' target, and subsequent experiments with the Whitworth guns, we have been enabled to deduce the formula for the penetrative power of steel projectiles as exhibited in the foregoing remarks.

Digitized by Google

TABLE III. — COMPARISON OF THE WORK DONE IN FOOT POUNDS ON DIFFERENT TARGETS.

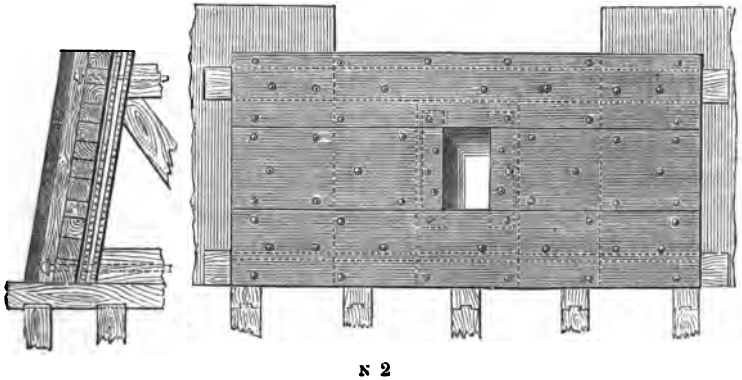
| Target | Weight of Shot striking Target in lbs. | Work done on Target | |
|---|---|---|---|
| | | Per Square Foot Foot lbs. | Total Foot lbs. |
| Thorneycroft 8-inch shield . . | 1,253 | 242,316 | 29,078,000 |
| Thorneycroft 10-inch embrasure | 1,511 | 492,933 | 37,140,000 |
| Roberts' target . . . . | 946 | 822,000 | 19,726,000 |
| Fairbairn's target . . . | 1,024 | 324,000 | 23,311,000 |
| 'Warrior' target . . . | 3,238 | 312,800 | 62.570,000 |
| 'Lord Warden' target . . | 2,208 | 333,546 | 60,038,281 |
| The Committee's target . . | 6,410 | 620,493 | 124,098,780 |

It must be observed that the 'Lord Warden' had an increased thickness of plates and timber, and a proportionate increase of weight per square foot of surface to that of the 'Warrior' as follows:—

The 'Lord Warden' weighing 483 lbs. per square foot.
And the 'Warrior' only 341 ,,
Making a difference of 142 ,,
In favour of the resisting powers of the 'Lord Warden.'

The form of the 'Lord Warden' target was somewhat different from that of the 'Warrior,' inasmuch as it had a plate 1½ inches thick between the 10-inch backing and the solid frames of the ship 12 inches thick; this, with the interior lining of 8 inches, and the armour plate 4½ inches, gave for the thickness of iron 6 inches, teak and oak 2 feet 6½ inches, making a total thickness of 3 feet, as shown in fig. 63, Chap. IX.

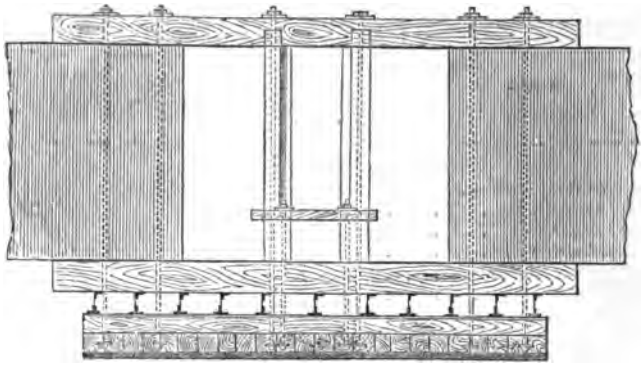
Fig. 64.





Digitized by Google

Fig. 65.



In the 'Warrior' the thickness of iron is 5¼ inches, and of teak and oak 1 foot 10¼ inches, making the total thickness 2 feet 3½ inches, as shown in fig. 64, which accounts for the superior weight of the 'Lord Warden'—142 lbs. per square foot above that of the 'Warrior.'

Comparing the weight of shot and shell discharged against each of these targets and the amount of work done, we have:—

For the 'Lord Warden,' 2,208 lbs.—say 2,200 lbs.
For the 'Warrior,' 3,338 „ „ 3,340 „

In this comparison it would appear that the 'Warrior' target sustained in weight of shot fired from separate guns, and in salvoes of three 100-pounders, above one-half more than the weight discharged at the 'Lord Warden;' but the work accumulated in the shot was not in the same proportion, being only—

In the case of the 'Warrior' . . 62,570,000 foot-pounds.
In the case of the 'Lord Warden' . 60,038,281 „

During the experiments on the resisting powers of plates of varied forms and thicknesses, a great number of guns of different calibre were employed from a rifled wall-piece of only 0·344 lbs. to a 600-pounder. The following table gives the results obtained from most of the guns, including the initial velocities of the shot and the work accumulated collectively in the entire weight of shot discharged on the targets:—

Digitized by Google

TABLE IV.—SUMMARY OF RESULTS.

Showing the Sizes of the Guns; Nature of the Projectiles and Work accumulated in the Shot at the Moment of Discharge.

| Description of Gun | Description of Shot | Material of Shot | Weight of Shot | Diameter of Shot | Charge of Powder | Initial Velocity of Shot in Feet per Second | Work accumulated in Shot |
|---|---|---|---|---|---|---|---|
| | | | lbs. | inches | lbs. | | |
| Wall-piece . . | Cylindrical flat-headed | Steel | 0·344 | 0·935 | .. | 1,141 | 6,954 |
| 6-pounder Armstrong | Solid | Cast iron | 6·25 | 2·53 | 0·75 | 1,168 | 132,400 |
| 12 " " | " | " | 11·56 | 3·02 | 1·75 | 1,155 | 239,500 |
| 25 " " | " | " | 24·81 | 3·77 | 3·13 | 1,169 | 526,500 |
| 40 " " | " | " | 41·20 | 4·77 | 5·00 | 1,164 | 866,800 |
| 40 " " | Shell | " | 43·00 | 4·77 | 5·00 | 1,140 | 867,700 |
| 40 " " | Solid | Wrought iron | .. | 4·77 | 5·00 | | |
| 68 " Smooth bore | " | Cast iron | 66·25 | 7·92 | 16·00 | 1,579 | 2,565,000 |
| 68 " " | Shell | " | 50·00 | 7·92 | 16·00 | 1,790 | 2,488,000 |
| 100 " Armstrong | Solid | " | 110·00 | 7·02 | 14·00 | 1,125 | 2,162,000 |
| 100 " " | " | " | 200·00 | 7·02 | 10·00 | 705 | 1,544,000 |
| 100 " " | Shell | " | 104·00 | 7·02 | 12·00 | 1,166 | 2,196,000 |
| 120 " " | Solid | " | 126·00 | 6·94 | 18·00 | 1,175 | 2,701,000 |
| 150 " " | Spherical | " | 108·75 | 9·17 | 25·00 | 1,532 | 3,781,113 |
| 300 " " | " | Steel | 168·25 | 10·43 | 50·00 | 1,593 | 6,629,806 |
| 600 " " | Spherical shot | " | 344·4 | 13·24 | 90·00 | 1,708 | 15,636,982 |

From the above will be seen the power and character of the ordnance employed; and in order to ascertain the effect of having the plates well supported behind, a great number of experiments were made with almost every description of backing, from solid iron and granite to every description of timber, paper, felt, &c. The effects produced by the different forms and weight of shot were measured by the depth of indentation, and the volume of metal displaced by the blows, as recorded in the following results taken from the 12, 40, and 100-pounder guns:—

TABLE V.—EXPERIMENTS WITH PLATES SUPPORTED BY BACKING.

| Description of Gun | Nature of Backing to Wrought-iron Plates | Thickness of Plate | Depth of Indentation | Volume of Metal displaced by Shot | Remarks |
|---|---|---|---|---|---|
| | | inches | inches | cubic inches | |
| 12-pounder Armstrong | Cast iron . . | 2½ | 0·5 | 0·7 | No damage |
| | Fir, cork, and bitumen . | 2½ | 0·6 | 1·0 | Two bolts started |
| | Oak . . . | 2½ | 0·65 | 1·2 | Bolts started |
| | Granite . . | 2½ | 0·55 | 0·8 | No damage |
| 40-pounder Armstrong | Cast iron . . | 2½ | 0·9 | 3·35 | Hit on bolt |
| | Fir, cork, and bitumen . | 2½ | Through | | |
| | Oak . . . | 2½ | Through | | |
| | Granite . . | 2½ | 0·6 | 1·6 | No damage |
| 100-pounder Armstrong | Cast iron . . | 2½ | 1·75 | 16·0 | Two cracks to edge |
| | Granite . . | 2½ | ... | ... | Struck near corner, and broke piece away |

Digitized by Google

In the above table the superiority of the rigid backing is manifest; but to ascertain the protection afforded by the backing, we may compare the following mean values for plates without backing :—

TABLE VI.—MEAN VALUE OF INDENTATIONS OF PLATES WITHOUT BACKING.

| Description of Gun | Thickness of Plate | Volume of Metal Displaced by the Shot | Remarks |
|---|---|---|---|
| | inches | cubic inches | |
| 12-pounder Armstrong | 2·0 | 6·3 | |
| 40 " " | 3·0 | 17·9 | |
| 100 " " | 4·5 | 27·2 | |

As the indentation is far greater without than with backing, it is manifest that a considerable protection is afforded to the plate by a rigid backing. In regard to the other backings, it must be remembered that the maximum thickness of penetration for a 40-pounder shot is only 2·82 inches, and that in these experiments that projectile actually passed through a 2½-inch iron plate. Hence very little additional resistance, if any, is obtained by placing oak or elastic backings behind iron plates. The experiments with Mr. Fairbairn's target, however, show that with wood placed in front of iron a considerable addition of strength is obtained. The result was, that with the 40-pounder Armstrong gun 4·3 inches of iron were displaced when the plate was naked, but only 1·1 inch when covered with 4 inches of elm. The result wants the confirmation of more extended experiments.

It will not be necessary to follow the experiments further in detail, as sufficient data were obtained to prove that a perfectly sound and rigid backing was essential to the support of the plates, and the nearest approach to that desideratum in a ship is teak or teak and oak. Mr. Fairbairn constructed two targets, one called the Fairbairn and the other the Committee's target, composed entirely of iron, for the exclusive purpose of ascertaining whether or not the wood backing could be entirely dispensed with. It will not be necessary to give further results of the experiments on these targets, as they were decidedly conclusive in showing the necessity of some support to the plates from

Digitized by Google

behind, or some elastic medium to lessen the vibration and deaden the blows, which seriously injured the bolts and fastenings, causing them to snap from the jar and force of the shot as it struck the plate.

11. Having described the nature of the targets and the quality of the plates, we have next to direct attention to the quality of the shot. It has already been stated that cast iron and wrought iron are not materials calculated to make any serious impressions upon armour-plates, and nothing has yet been found to answer that purpose better than hardened steel. Cast iron, such as that prepared by Dr. Price, and case-hardened shot, as prepared by Captain Palliser, may answer the purpose in some cases; but it appears questionable whether cast iron, however well prepared, will ever act against armour-plates with anything like a damaging effect, or whether it can be made to hold together and not break in pieces when the blow is struck upon the plates. In our opinion, this will be more or less the case when a ship is in action, and particularly at close quarters; no ship should, therefore, go to sea without a large supply of steel shot and shell when intended for the attack of iron-plated vessels.

To illustrate the facts above recorded, the author was directed to examine and determine experimentally the resisting powers of the different kinds of shot, and to enable him to do so, a great variety of shot were submitted for experiment. Those only from Dr. Price's prepared cast iron indicated superior powers of resistance, and as their tenacity was nearly double that of ordinary cast iron, it may be interesting to give some of the results as recorded in the author's work on 'Iron Manufacture,' pages 229 *et seq.*

The extraordinary resisting powers of bars cut from three specimens of cast iron (prepared by Dr. Price for experiment at Shoeburyness) to a tensile strain, are of that important character which requires careful investigation. In former times, when vessels were entirely constructed of wood, and when thick plates of armour were never dreamt of for purposes of resistance, cast-iron shot was equally good and effective in its results as the hardest steel. Now things are widely different, for instead of 18 to 20 inches thickness of oak, which is easily perforated, we have to go through a solid 4½ or 5-inch wrought-

Digitized by Google

iron plate of the toughest description, before the interior of the ship is reached. In firing at timber-built vessels there is no injury done to cast-iron shot, whatever may be the thickness; but in iron-cased ships the injury done to cast-iron shot is much greater than that which it inflicts upon the plates. On referring to our former experiments, we find that a cast-iron shot breaks in pieces, and loses a considerable amount of its *vis viva* when it strikes at a high velocity against a thick wrought-iron plate; and in order to render it more tenacious and more destructive in its effects, it is equally important that the shot should be as irresistible as the plate should be invulnerable. It is true that we may never attain so important a desideratum in cast iron as to make shot of that material indestructible, but we may, by proper attention to its mechanical and chemical elements, greatly improve its powers of resistance; and the following experiments on Dr. Price's compound mixture clearly show, as a beginning, what has been done, and what may yet be expected by a careful investigation of a subject of such great importance to the country, and of no small value as regards the improvement of projectiles.

The average tensile strength of cast iron has been found to be about seven tons per square inch. In the first experiment on the metal from which this shot was cast, it appeared so much above the ordinary tenacity of cast iron that another piece was cut out, near the centre, for the purpose of correcting what appeared to be the anomalous condition of the first experiment. It will, however, appear obvious that the metal, taken as a measure of its tenacity, is, in the mean of the two experiments, considerably above that of ordinary cast iron, being in the ratio of about 12 : 7, or as 1·77 : 1 in favour of the shot. The appearance of the fracture is a close finely-granulated structure, crystallization bright and clear.

Summary of Results taken from the Experiments as follows:—

| Experiment | Specimen | Tons Per Square Inch | Elongation per Unit of Length |
|---|---|---|---|
| 1 | W | 13·125 | ·00950 |
| 2 | W | 11·714 | ·01500 |
| 3 | BW | 14·762 | ·01333 |
| 4 | B | 15·189 | ·01131 |
| | Mean . | 13·697 | ·01229 |

being nearly double the strength of ordinary cast iron.

Digitized by Google

Similar results, although not to the same extent, are obtained in the following summary of experiments on compression. They also indicate greatly superior powers of resistance to a crushing force, and approximate closely to the inferior descriptions of wrought iron as regards a tensile strain, and above that of cast iron to compression :—

SUMMARY OF RESULTS.

| Experiment | Specimen | Crushing Strength in Tons | Mean Compression per Unit of Length |
|---|---|---|---|
| 5 | B | 60·037 | ·084 |
| 6 | WB | 59·237 | ·170 |
| 7 | W | 52·837 | ·098 |
| | Mean . | 57·370 | ·117 |

From the above summary of experiments on compression and tension, we derive these important facts—namely, that cast iron may be increased in the strength of its molecular construction to an extent considerably beyond that of ordinary cast iron, and this may be done at a very moderate cost, by adopting the admixture of wrought-iron turnings, as first adopted by Mr. Stirling; or it may be accomplished on the principle adopted by Dr. Price, which gives still higher powers of resistance. It is therefore important not only that we should ascertain the best description of armour-plates calculated to resist projectiles of any description, but it is equally important that we should employ the most powerful description of shot to overcome that resistance.

Now, we have already determined the kinds of shot and shell best adapted for the penetration and perforation of iron plates; but as cast iron, from its cheapness, facility of moulding, etc., can be produced at a comparatively small cost, it is desirable to ascertain in what manner and to what extent its tenacity can be increased, so as to approximate to the strength of wrought iron or homogeneous metal.

The present state of our knowledge is limited in this respect, and a series of well-conducted chemical and mechanical experiments to determine these points would be highly valuable.

In the above experiments it has been shown that the cast-iron shot prepared by Dr. Price is of a high order, and that cast iron may be toughened either upon the Stirling principle,

Digitized by Google

by an admixture of wrought iron, or by Dr. Price's method, which gives such good results. The object to be attained appears to be, that the shot should be sufficiently tenacious to resist the effects of impact, when it comes in contact with the plate; or, in other words, it should be able to deliver the whole of its *vis viva* upon the armour-plate without breaking. This cannot be expected from shot composed of this description of material, but it may be greatly increased in tenacity, and rendered much more destructive in its effects, than if made of ordinary cast iron.

We have shown that cast iron is greatly improved in strength by an admixture of wrought iron, but we have not noticed what may yet be done by a judicious process of decarbonisation, where the metal is in a perfectly fluid state, and at a high temperature.

A process of this kind, either upon the Bessemer or some other equally effective system, would convert the metal into a species of steel at a comparatively small cost, with immense advantage to the tenacity of the metal. In this preparatory state it might be cast, as in all fluid metals, into the shape and form required for ordnance of any description. For particular purposes, and for special service, hardened steel is the only material calculated for the perforation of armour-plates; but this material is expensive, as it has to undergo several elaborate processes of hammering, heating, and rolling, before it is sufficiently consolidated to answer the purpose of powerfully resisting shot that will not fracture by impact.

It is immaterial whether this metal is prepared in the puddling furnace or in the Bessemer kettle; to give it solidity it must be rewrought and consolidated under the hammer, to attain the required density by a close adherence of its crystalline structure. These processes are necessary to make it sufficiently adherent to resist blows at the point of contact, and to deliver its entire force upon the plate without the risk of fracture.

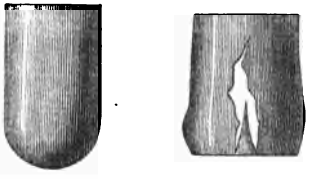
12. In further illustration of this subject it may be interesting to show the effects of statical pressure on different kinds of shot to a force tending to crush them, and the forms they assume under pressure. A series of experiments were made to ascertain certain facts connected with the experiments on impact at

Digitized by Google

Shoeburyness, and to deduce from actual pressure the force required to break up shot composed of cast iron, wrought iron, and steel.

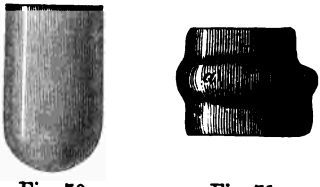
To accomplish this, and to arrive at correct results, the whole of the specimens were made of the same dimensions as those used in the wall-piece gun—1½ inch long, and 0·83 inch in diameter. The forms of these specimens, before and after experiment, were as shown in the following sketches :—

Fig. 66. Fig. 67.



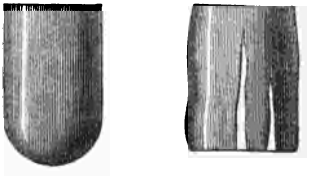
Cast iron, before and after experiment.

Fig. 68. Fig. 69.



Wrought iron, before and after experiment. This had a covering of lead, which took the form *a* as the weights were laid on.

Fig. 70. Fig. 71.



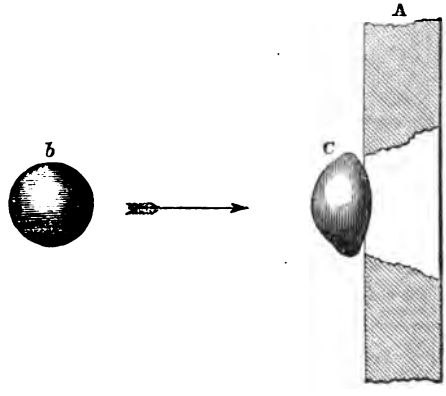
Hardened steel, before and after experiment.

From these sketches it will be seen that the fracture of the shot from statical compression bore a strong resemblance to what was obtained from impact when fired from a gun, and the effects produced on the different materials appear to be in accordance with the gun experiments at Shoeburyness, more particularly as respects the wrought-iron shot, which was flattened; and the same result was apparent whether the shot penetrated the plate or not, the shape of the hole being that of the shot in its enlarged and compressed state. From the recent experiments with the 150-pounder smooth-bore gun with a wrought-iron shot against

Digitized by Google

Mr. Scott Russell's target, the same remarkable results were obtained as in that of statical pressure; the shape of the ball having the appearance of a lump of flattened lead, as shown in the sketch (fig. 72), which represents a portion of the target. *A*, the target plates, 8¼ inches thick; *b*, the spherical wrought-iron shot, 10·372 inches diameter as it left the gun; and *c*, the shape after it had struck the target and flattened to 12·969 inches in its largest diameter, which corresponds with the exact size of the part that was driven out of the target. This experiment presents some curious and interesting facts, namely, the resistance of the target which was penetrated with a hole clean through the whole thickness of the plate without the ball passing through. It fell dead 5 yards from the foot of the

Fig. 72.




target, after inflicting the blow and driving out the full area of its increased dimensions.

On a careful examination of the hole and the shot it was found that the charge of 50 lbs. of powder was just equal to force out a volume of the target equal to its enlarged dimensions, but unable to go right through, owing to a thin web which was formed by the blow on the compressed edge of the ball. This, on measurement, was found to be rather larger than the hole made in the plate.

Looking at these facts, and supposing that the shot had been perfectly rigid and indestructible, it would have gone through the target with perfect ease, as the number of inches to force

Digitized by Google

TABLE VII.—SUMMARY OF RESULTS.

| No. of Experiment | Description of Shot | Length in Inches | Diameter in Inches | Area in Inches | Weight laid on in lbs. | Compression per Unit of Length in Inches | Pressure per Square Inch in lbs. | Pressure per Square Inch in Tons | Work done during the Experiment in Foot Pounds per Square Inch | Means of ditto | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Cast iron, flat-ended . . | 1·5 | ·875 | ·6013 | 73,428 | ·08 | 122,115 | 54·51 | 902·6 | 776·8 | Crushed |
| 2 | „ „ . . | 1·5 | ·83 | ·541 | 68,052 | ·053 | 125,787 | 56·13 | 650·9 | | „ |
| 3 | „ round-ended . | 1·72 | ·85 | ·5674 | 35,540 | ·122 | 62,636 | 27·96 | 899·7 | 821·9 | „ |
| 4 | „ „ . . | 1·72 | ·95 | ·7088 | 40,916 | ·139 | 57,725 | 25·77 | 744·1 | | „ |
| 5 | Wrought iron, flat-ended . | 1·5 | ·875 | ·6013 | 94,412 | ·193 | 157,013 | 70·09 | 2542·8 | 3441·4 | Compressed |
| 6 | „ „ . | 1·5 | ·83 | ·541 | 94,412 | ·37 | 174,513 | 77·9 | 4340·1* | | „ |
| 7 | „ round-ended . | 1·72 | ·85 | ·5674 | 75,220 | ·225 | 132,569 | 59·18 | 2996·1 | 2200·6 | „ |
| 8 | „ „ . | 1·72 | ·95 | ·7088 | 64,468 | ·168 | 90,953 | 40·6 | 1405·2* | | „ |
| 9 | Hardened steel, flat-ended . | 1·5 | ·83 | ·541 | 145,756 | ·026 | 269,419 | 120·27 | 1608·1 | ... | „ |
| 10 | „ round-ended | 1·72 | ·85 | ·5674 | 114,980 | ·1162 | 202,643 | 90·46 | 2515·0 | ... | Fractured |
| 11 | Leaden ball, flat-ended . | 1·5 | ·95 | ·7088 | 7,078 | ·393 | 9,985 | 4·45 | 270·9 | ... | Compressed |
| 12 | „ round-ended . | 1·72 | ·95 | ·7088 | 7,078 | ·4 | 9,985 | 4·45 | 290·6 | ... | „ |

* These experiments on wrought iron cannot be relied upon, as the socket of the plunger broke in both cases.

Digitized by Google

through was considerably less, being in the ratio of 10 : 12·5; or, in other words, the perfectly rigid ball would have to punch out of the target an area of 71·5 square inches, whereas the compressible one had one-fifth more duty to perform in cutting its way through 122·7 inches, being in the ratio of the circumferences of the punches.

A remarkable coincidence exists between the results of the gun experiments at Shoeburyness and those obtained from actual pressure. In both cases the experiments indicate the law on which the compression of the shot and the perforation of the plate depend; it, moreover, shows that in every case where a vessel can run alongside of an enemy, or within a range of from 100 to 200 yards, a hardened-steel shot is then available, and will do more execution than one made of either cast or wrought iron.

Two series of interesting experiments made with the Whitworth gun completely verify these remarks as regards the efficiency and remarkable penetrating power of hardened steel, as compared with any other description of shot. The same remarks apply to shells, which, made of steel on the Whitworth principle, are calculated to produce extraordinary powers of penetration, accompanied with the most destructive effects in the bursting of the shell.

From these results, and the coincidence which appears to exist between the force of impact and statical pressure, we arrive at the conclusion that every description of shot and shell intended for the penetration of armour-plates should be of *hardened steel*, sufficiently tenacious not to break in pieces, and yet so hard as to resist compression.

The preceding summary, Table VII., exhibits the results of compression on cast and wrought iron, steel, and lead, as deduced from the experiments.

In the experiments on the wrought iron, the flat-ended steel, and the lead specimens, no definite termination was arrived at, the material being more or less compressed without any fracture ensuing: hence it is difficult to draw conclusions from these results, beyond the great amount of work expended in compressing the wrought-iron specimens, amounting in one case to 4,340 foot-pounds, or nearly twice as much as was required to fracture the round-ended specimens of steel. On the other

Digitized by Google

hand, the low statical resistance of lead corresponds with a dynamical resistance almost equally low.

The remaining results may be stated as follows:—

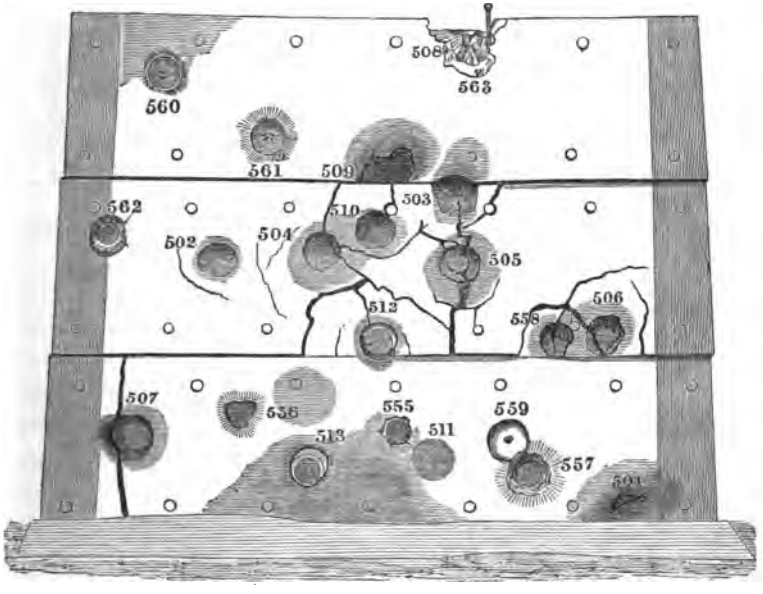
| | Foot Pounds per Square Inch to produce Rupture. | |
|---|---|---|
| Cast iron, flat-ended . . . . . | 902·6<br>650·9 | mean 777. |
| Cast iron, round-ended . . . . . | 899·7<br>744·1 | mean 882. |
| Steel, round-ended . . . . . | 2515 | |

On referring to Table VII., it will be observed that the work required to crush similar specimens of cast iron is nearly the same, whether the ends be rounded or not, the round-ended requiring rather more work to be expended than those with the flat ends; it is therefore obvious that there is no analogy between the law deduced for statical forces by Professor Hodgkinson, and the law regulating the dynamic resistance.

The mean resistance of the specimens of cast iron is 800 foot-pounds per square inch, that of the specimen of steel 2,515 foot-pounds, or rather more than three times as much.

In further illustration of this subject, we may refer to the

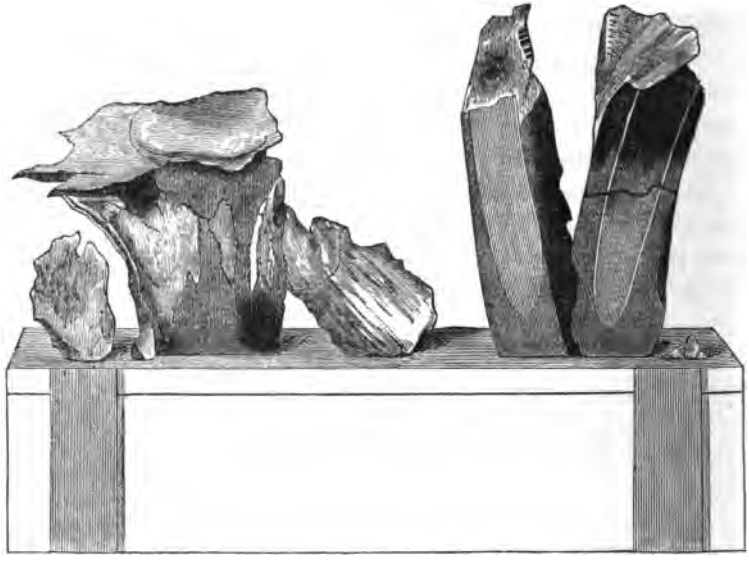
Fig. 73.




Digitized by Google

'Warrior' target, submitted to the attack of shot composed of different materials and of different forms. The object of this experiment was to determine the comparative effect of these projectiles fired against iron armour-plates, both as regards the amount of indentation produced on the plates and the effects of impact on the shot. These are shown in fig. 73 and fig. 74 respectively. The indentation produced in the plate was carefully ascertained and recorded, and where the shot was distorted or fractured by the blow, the injury was described, and drawings

Fig. 74.



showing the nature of the fracture made. Fig. 74 illustrates the form and nature of the fracture of some of these shot.

Table VIII. gives full particulars of the experiment against a section of the 'Warrior' target, and here it will be observed that all the different qualities of shot were employed in order to test not only the depth of indentation, but to establish some fixed law in regard to the distortion and breaking-up of the shot. These results are given in Table VIII. and the remarks which follow.

Digitized by Google

TABLE VIII.—REPORT OF AN EXPERIMENT, SHOWING THE EFFECT OF SHOT FIRED AGAINST THE 'WARRIOR' SECTION,—TARGET NO. 14—AND ALSO THE INJURY DONE TO THE SHOT.

| No. of Round | Photographic Number | Nature of Ordnance | Projectile | | | | | Charge in lbs. | Elevation | Range in Yards | Deflection | Effects | | Velocity at 510 Feet |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Nature | Weight in lbs. | Form | Length | Diameter | | | | | Depth of Indent in Inches | Diameter of Indent in Inches | |
| | | | | | | | in. | | | | | | | |
| 1 | 555 | 40-pounder Armstrong rifled gun | Steel solid shot | 37·25 | Cylindrical F.E. slightly concave | 7·30 | ... | 5 | ... | 100 | 8′R | 1·25 | 6· | |
| 2 | 556 | ,, ,, | ,, | 37·125 | ,, | ,, | ... | ,, | ... | ,, | .. | 1·4 | 6·8 × 6·5 | |
| 3 | 557 | 68-pounder smooth-bore gun | Cast-iron service shot | 65·5 | Spherical | ... | 7·91 | 16 | 20′ | 200 | ... | 2·5 | 8·5 | 1413·8 |
| 4 | 558 | ,, ,, | Wrought-iron solid shot | 71·0 | ,, | ... | ,, | ,, | 22′ | ,, | ... | ... | ... | 1409·9 |
| 5 | 559 | ,, ,, | ,, | ,, | ,, | ... | ,, | ,, | 20′ | ,, | ... | 3·1 | 9· | 1385·0 |
| 6 | 560 | 110-pounder Armstrong rifled gun | Cast-iron solid shot | 66·3 | Cylindrical R.E. | 11·5 | ... | ,, | 15′ | ,, | 10′R | 2·45 | 8· × 7·5 | 1461·0 |
| 7 | 561 | ,, ,, | O. S. C. steel solid shot | 65·4 | Cylindrical with cast-iron head | 10·75 over all steel 5·25 cast-iron 5·5 | ... | ,, | ,, | ,, | ,, | 3 at deepest and 1·4 at shallowest | ... | 1413·9 |
| 8 | 562 | ,, ,, | Makin's steel solid shot | 99·5 | Cylindrical with spike end | 11·7 over all | ... | 14 | 23′ | ,, | ,, | ... | 8·5 × 9 | 1178.8 |
| 9 | 563 | ,, ,, | ,, | 103·0 | ,, | 11·3 | ... | ,, | 24′ | ,, | ,, | ... | ... | 1172·8 |

Digitized by Google

*Remarks on the foregoing Table.*

1. Struck the lower plate 1 foot 4·5 inches from the top, and 6 inches from the left side; the shot 'set up' and remained in the target, projecting 5·25 inches; the shot was not cracked; one fastening bolt broken.

2. Struck the lower plate 1 foot 1·5 inches from the top, and 3 feet 6 inches from the left side; an old crack at 2 inches from the point of impact, increased 6 inches in length; the shot which was marked T broke into four pieces.

3. Struck the lower plate 1 foot 4 inches from the bottom, and 3 feet 5 inches from the right side; small crack on face of indent, two radiating cracks from an old indent at 1 foot 3 inches to the left of present one, and a crack 2 feet long at 1 foot 2 inches from the right of indent.

4. Struck the centre plate, and therefore no use for comparison.

5. Struck the lower plate 8·5 inches (measuring from centre to centre) from Round No. 3; two small cracks on the face of indent, and a wide crack 29 inches long across the indent of No. 557; one rib and one rivet broken. The major diameter of the shot after impact was 9 inches.

6. Struck the upper plate 1 foot from the top, and 1 foot 10 inches from the left side; small crack on face of indent, and two bolts in the upper row started 0·2 inches and 0·5 inches respectively.

7. Struck the upper plate 11 inches from the bottom on a bolt, which started 0·5 inches; a crack 0·5 inches long from bolt-hole, a crack across indent, and a crack 0·5 inches wide round two-thirds of the circumference of indent. The shot was cracked at the side, and was set up 0·75 inches. The false head broke off before the shot struck the target.

8. Struck the centre plate 1 foot from the left side and 11 inches from the top, broke a hole in plate, the greatest depth being 6·7 inches; a crack 7 inches long at 6 inches to the right of indent; one rib broken; the plate buckled a good deal, and was off the backing 1·8 inches at bottom, and 1·5 inches at top on the left side. The shot set up 1·2 inches, and the shoulder

Digitized by Google

was broken off round the entire circumference, but it was otherwise uninjured.

9. Struck the upper plate 9 inches from the top on a bolt, and broke away a portion of plate measuring 15 × 12 inches; a length of 1 foot 7 inches of the front layer of wood backing torn away; the spike of the shot was broken off, and also the shoulder for half the circumference. The shot was not at all 'set up.'

The work in the shot was as follows:—

| | Foot-Pounds |
|---|---|
| No. 557. Cast-iron service shot, from 68-pounder smooth-bore gun, 16-lb. charge | 2,061,877 |
| No. 559. Wrought-iron shot, from 68-pounder smooth-bore gun, 16-lb. charge | 2,128,031 |
| No. 560. 66-lb. cast-iron shot, from 110-pounder rifled gun, 16-lb. charge | 2,199,773 |
| No. 561. 65-lb. steel shot, from 110-pounder rifled gun, 16-lb. charge | 2,027,765 |
| No. 562. 99-lb. steel shot, from 110-pounder rifled gun, 14-lb. charge | 2,149,882 |

A comparison of No. 560 and No. 562 shows the superiority of steel over cast-iron shot, in consequence of the great amount of loss arising from the breaking-up of the latter; for although the work in No. 560 (a cast-iron shot) was 2,199,733 foot-pounds, the damage to the plate was only an indent of 2·45 inches; whereas in the case of No. 562 (a steel shot), although a less amount of work was stored up in the shot, viz. only 2,149,882 foot-pounds, or a difference of 49,891 foot-pounds, a much larger amount of damage was caused to the plate—viz., a penetration of 4½ inches; and although a portion of this may be due to difference of form, and also to the inferior quality of the centre plate, it is doubtless chiefly to be attributed to the superior metal of which the shot was composed.

The experiment quite corroborates the opinion previously entertained of the greater effect of properly-tempered steel shot, as compared with cast or wrought iron. The steel shot used in the eighth round was of great toughness and strength; it suffered but little from the blow, and nearly the whole work was expended on the plate, as was evident from the great damage done.

Rounds Nos. 560 and 561, fired from the 110-pounder rifle-gun, show that this gun is capable of being used with light shot so as to be as effective at short ranges as the 68-pounder.

The conditions which would appear desirable in projectiles, in



Digitized by Google

order that the greatest amount of work may be expended on the armour-plate, are—1st. Very high statical resistance to rupture by compression: in this respect wrought iron and steel are both superior to cast iron; in fact, the statical resistance of steel is more than three times, and that of wrought iron more than two-and-a-half times, that of cast iron; lead is inferior to all the other metals experimented upon. 2ndly. Resistance to change of form under great pressures; in this respect hardened steel is superior to wrought iron; cast iron is inferior to both.

The shot which would effect the greatest damage to a plate would be one of adamant, incapable of change of form; such a shot would yield up the whole of its *vis vivâ* to the plate struck; and, so far as experiment yet proves, those projectiles which approach nearest to this condition are the most effective.

Digitized by Google

# CHAPTER XI.

## ON THE PRACTICAL CONSTRUCTION OF IRON SHIPS.

1. The construction of iron ships, in so far as relates to the distribution of the material and other considerations connected with the war and mercantile navies of this country, rank probably amongst the most important investigations of the present age. The state of transition in which this and all other maritime nations are placed, imperatively demands the confirmation and appliance of general laws founded on the unerring principles of truth, and to elaborate and carry these laws into effect is the object of this inquiry—such, in fact, as may lead to increased security and the development of new and important principles in this particular branch of industry. It is now more than thirty years since iron was found to be a material of great value in shipbuilding, and it has taken that time to remove many prejudices, and to convince the public mind that an iron ship is stronger, more durable, and ultimately cheaper than one composed of wood. The difference and comparative values have already been shown, and the author of this work has laboured incessantly to prove the advantages of a more extended use of iron in its application to the construction of ships, buildings, bridges, and other purposes where it can be usefully and economically employed; and now that the Government have taken up the subject, he is the more desirous that iron, as a material of construction in the Navy, should be applied upon fixed principles calculated to promote the interest of the country and establish an improved and efficient system of construction. On these important points we have endeavoured to bring the whole extent of our knowledge to bear upon the subject, and we have not hesitated to collect and record from our own and other sources such experimental facts as are calculated to

Digitized by Google

enhance the value of our constructions, and to render them useful in all those appliances to which iron, as a material, is so admirably adapted.

To arrive at satisfactory results in this respect, it is essential that we should become acquainted with the principles on which the security of the structure depends. We should also know the purposes, form, and other conditions for which it is intended, and, above all, we should be conversant with the strains, endurances, and other casualties to which it may be subjected. Having made ourselves acquainted with all these points, the next consideration is to select the best and strongest material calculated to meet those requirements. In shipbuilding, as in many other constructions, these are considerations of immense importance, and hence the necessity of knowledge founded on correct principles to ensure success in the first instance, and sound practical experience in the second.

In submitting these remarks we do not wish it to be understood that we are in the possession of all this knowledge—on the contrary, we are very deficient; but having laboured for a long series of years in this department of practical science, we are every day more convinced that, in order to arrive at sound construction, we must not leave it to chance, nor must we intrust it in the hands of pretenders. It is for these reasons we have ventured to notice not what are but what should be the qualifications of shipbuilders, engineers, and architects, in order that the work may be well executed, and that the property of the nation may be placed on a footing of increased security and endurance.

Impressed with the importance of these remarks, we have taken some pains in this work not to depend on the judgment of others, but to found our opinion as much as possible on the results of experiment in regard to the properties and distribution of the material, and its combination with other material; and moreover we have, in so far as the strength of iron applies to ships of war, given abstracts from our own experimental researches on the resistance of armour-plates, properties of projectiles, and other data calculated to guide the naval architect in the appliance and combination of material in the elementary principles of construction.

Digitized by Google

With these impressions, and a knowledge of their importance, we now proceed to show what is necessary to be observed in the construction of iron ships, and other essentials as applied to them. In this arrangement we have, first, to consider the general outline of the ship as comprised in length, breadth, and depth; and, secondly, the service for which it is intended.

2. There are three classes of vessels which require consideration—namely, sailing-vessels, steamers, and ships of war, which combine the qualities of both. To the whole of these vessels the same principle of construction appertains as regards strength, as they have to float on the same element and encounter the same force of wind and sea. They are, however, widely different when we consider the objects for which they are intended. In the case of sailing-vessels adapted as clippers for carrying passengers and cargo, or for both speed and cargo where a large surface of canvas is necessary, a fine entrance at the bows and a sharp run at the stern, including capacity at midships, are points essential to meet the requirements of speed and a suitable cargo.

In the construction of vessels of this class it may be useful to enumerate a few particulars, not so much as regards form, which may safely be intrusted to the builder, whose knowledge of the service is the best guide for securing to the owners an efficient and suitable vessel, adapted to the trade in which she has to be employed and the seas she has to navigate. What we have to accomplish in this place is to point out, in the use of

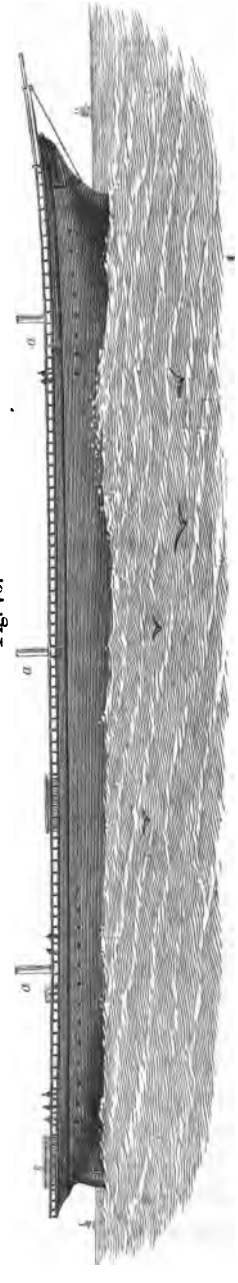


Fig. 75.

Digitized by Google

iron as the material of construction, how it should be applied, united, and distributed so as to secure the maximum of strength with the minimum of material; bearing in mind at the same time the object for which the vessel is intended, and the length of voyages she may be called upon to perform.

Let us, for example, endeavour to give the necessary details for the construction of a merchant sailing-vessel adapted for the trade between this country and India or America. Let figs. 75, 76, and 77 represent the sides and transverse sections of a ship, 264 feet long, 40 feet wide, and 38 feet deep.

In this and all other vessels of the larger class we are of opinion that the cellular construction and the double bottom, as shown in fig. 76 and fig. 77, are points of great importance as regards security and strength.

Fig. 76.

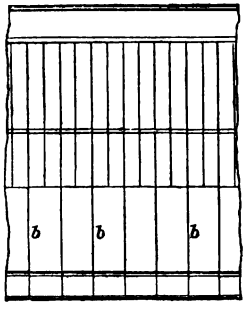
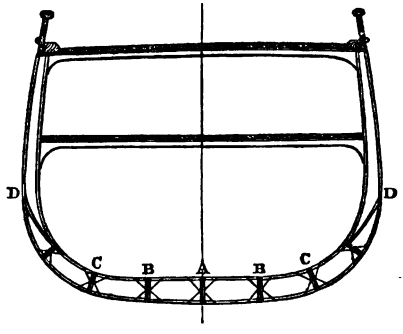



Fig. 77.

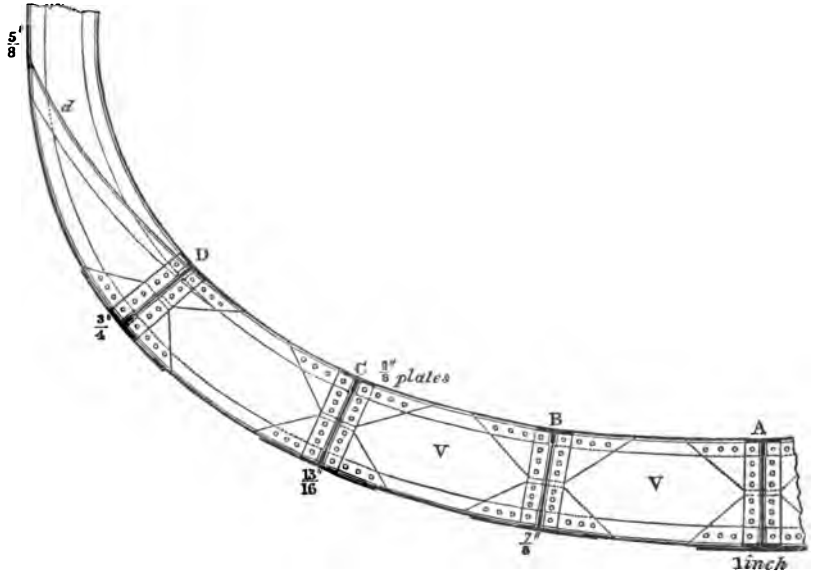



The first consideration in this construction is the transverse strength of the ship; and in fig. 77 the lines A, B, C, &c. represent longitudinal girders 3 feet deep, extending the whole length of the ship, or until they unite on each side of the central interior keel, or intersect each other as they converge upon the lines of the ship at the stem and stern. The keelson, A, is composed of a plate $\frac{3}{8}$ inch thick and 3 feet deep, chain-riveted at the joints, and attached to the bow and stern-posts; the angle irons are $5 \times 3\frac{1}{2} \times \frac{5}{8}$ inch below, and $3\frac{1}{2} \times \frac{3}{8}$ inch above. The others, B, C, &c., on each side are composed of $\frac{5}{16}$ inch web plates, and $4 \times \frac{1}{2}$ inch angle iron below and $4 \times \frac{3}{8}$ inch angle iron above. The frames or ribs (*b b b*, &c., fig. 76) are formed

Digitized by Google

simply of $5 \times 3\frac{1}{2} \times \frac{5}{8}$ inch angle iron, extending from the upper deck on each side till they join at D, the longitudinal frames, C C, to which they are secured and firmly riveted. Between C and B and B and A on each side, the same strength of angle iron is maintained between all the girders, forming rectangular cells. These cells may be transversely open between the bulkheads, which are plated and made watertight from the bottom of the cells to the lower deck on each side. Fig. 78, drawn to a scale of $\frac{3}{16}$ inch to the foot, shows the construction of the cells to their termination at *d*, where the double frames and ribs commence and extend to the upper deck. At the point *d*, where the cells terminate, it will be observed that the plate D, riveted to angle iron, closes up the cells and renders the whole watertight

Fig. 78.




throughout the whole length of the ship. It will be further noticed that the gusset-plates are riveted to the angle iron ribs, connecting them securely with the longitudinal keelson and double bottom.

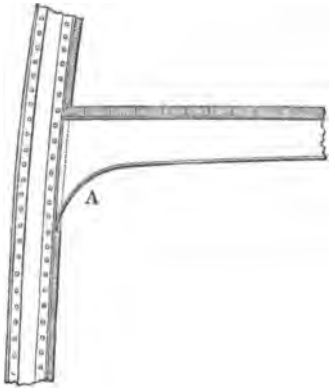
It will also be observed that this construction becomes the more valuable as the cells (v v) on each side may be formed into

Digitized by Google

water-tanks, or vessels containing water prepared for the purpose, and calculated to contain a constant and fresh supply during long voyages.

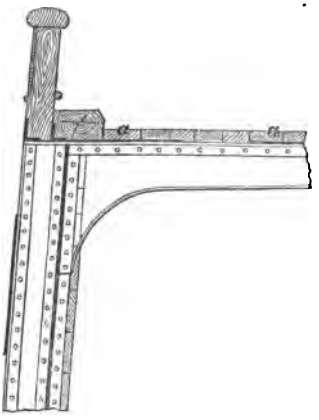
As respects the construction from D to the upper deck, it has been stated that the main ribs, which divide the cells transversely at regular distances of 4 feet, are continued up to the principal beams of the middle and the upper deck, to which they are united by rivets and firmly secured by gussets, as shown at A, fig. 79. Between these ribs, 4 feet asunder, are intermediate ribs of T iron, $5 \times 3 \times \frac{1}{2}$ inch, riveted to the sides, as shown in the longitudinal section, fig. 76; and they extend from the point D, where the double bottom terminates, to the upper deck. The T iron ribs are intended to stiffen the sides of the ship from that point upwards between the decks.

Fig. 79.




The plating or sheathing would vary in thickness from $\frac{7}{8}$ inch at the centre keelson to $\frac{5}{8}$ inch up the sides to the last plate on the top, which should be $\frac{3}{4}$ or $\frac{7}{8}$ thick in the middle, on account of giving increased resistance to the upper sides of the ship, and the transverse joints of these plates should be chain-riveted in order to resist tension as well as compression. The same mode of construction should be observed on the upper deck, and it will be necessary to have powerful stringer-plates, not less than $\frac{3}{4}$ inch thick (as shown at *a*, *a*, &c., fig. 80), and these being judiciously proportioned to the strains, as given in Chap. V., 'On the Strength and Distribution of the Material of Wrought-iron Plates and Frames, as applied to the Construction of Iron Ships.' The vessel so proportioned will have a sectional

Fig. 80.




Digitized by Google

area of iron on the upper deck and down to a depth of 8 feet on each side, equivalent to 450 square inches, which, added to the resisting powers of the wooden deck, will give the required section to match the double bottom of the hull, and closely approximate to the balance of the two resisting forces, on which depends the ultimate strength of the ship.

This, it will be observed, would form a strong and substantial vessel, carefully protected from absolute loss in case of accident, if stranded on a lee-shore, and perfectly secure in its resistance to strain in pitching and rolling in the heaviest sea.

In this calculation we are assuming the section of the bottom and the section of the top to be equal. This is, however, not the case, as we have only 450 inches of iron in the top section; but adding to this the deck planking, securely bolted to the cross-beams and crossed at the joints, we may safely raise the section to 600 inches, which, in practice, will meet every contingency in the balance of the two forces of tension and compression.

This distribution of the material exclusively relates to the section at midships; it is not, however, necessary to continue that section or thickness of plates to the extremities at the stem and stern, but to taper the stringer as well as the cellular construction from $\frac{7}{8}$ inch thick at midships to $\frac{5}{8}$ inch at both ends—or, in other words, to proportion the plates according to position from midships to the bows and stern, where the wear-and-tear are greater than in other parts.*

Having determined the position, form, thickness, &c. of the material which enters into the construction of an iron ship of this class, it may be of some importance to show how the different parts are prepared and united in order to attain their full value in combination, and, moreover, that each section should be calculated and adapted to the work it has to perform.

This proportioning of the parts tending to a finished whole is the acme of art in every construction, and it requires not only judgment, but knowledge of the properties of the material, and great experience, successfully to attain that important desideratum.

We are the more urgent on this point, as the law of proportion in ships requires that they should not be burdened with

* For further information on this subject, see Chap. V. page 65.

Digitized by Google

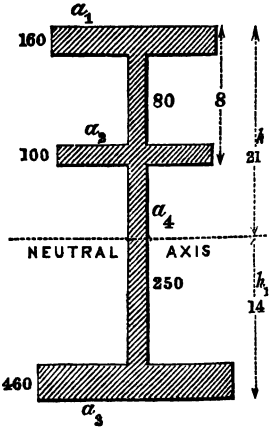
unnecessary material where it is absolutely doing serious injury by adding weight where it is not wanted, and where it has to be permanently supported; charging the structure, whatever it may be, with a load not its own—an incubus, in fact, which remonstrates and never relaxes in its reproaches till the structure is ultimately destroyed. We are no advocates for ships, bridges, boilers, and similar constructions being contracted for by weight, as the tendency on the part of the contractor is to offer low rates, and to make up for the deficiency in price by increase of weight. This system of sacrificing quality for weight is in boilers and bridges a general practice; and how frequently do we hear of ship plates as being synonymous with iron that is not to be trusted, and totally unfit for such a service! Assuming, however, that no seagoing vessel should have plates and angle iron which are not capable of sustaining a tensile strain of less than 20 to 22 tons per square inch, and assuming also that they are sound and ductile, we should then have, according to the construction referred to, the following proportions, viz.—

| | Square Inches |
|---|---|
| For the bottom section, from the centre keelson to *c* on each side, forming the cells and double bottom . . . . . | 460 |
| For the upper deck and 8 feet down the sides, including stringers, &c. . . . . | 340 |
| And taking the intermediate spaces between the double bottom and 8 feet below the upper deck at . . . . . | 280 |
| We have for the whole section at midships . . | 1,080 |

Now, supposing the material in the transverse section to be distributed as represented in the annexed diagram:—

| | Square Inches. |
|---|---|
| Bottom section, &c,. $a_3$ . . . | = 460 |
| Upper deck, $a_1$ . . . . . | = 160 |
| Lower deck, $a_2$ . . . . | = 100 |
| Sides, between the two decks . . | = 80 |
| Sides, from the lower deck to bottom | = 250 |
| | 1050 |

Length of the Ship, 240 feet; depth, 35 feet; distance between the upper and lower deck, 8 feet.




Digitized by Google

By formulæ (7) and (8), Art. 69, Chap. XIV., we have $a_1=160$, $a_2=100$, $a_3=460$, $a_0=80+250=330$, $D=35$, $a_2=8$, $K=1050$.

Distance neutral axis from the upper edge $= h$

$$=\tfrac{1}{1050}\left\{\left(\tfrac{330}{2}+460\right)35+100\times 8\right\}=21 \quad \ldots (7)$$

$$I_0=330\left\{\tfrac{1}{12}\times 35^2+(21-\tfrac{1}{2}\times 35)^2\right\}+160\times 21^2+100\,(21-8)^2$$
$$+460\,(21-35)^2=215348 \quad \ldots (8)$$

Then $M=\frac{s_1}{h_1} I_0$ or $\frac{s}{h} I_0$; and taking $s_1=20$ tons, $s=18$ tons.

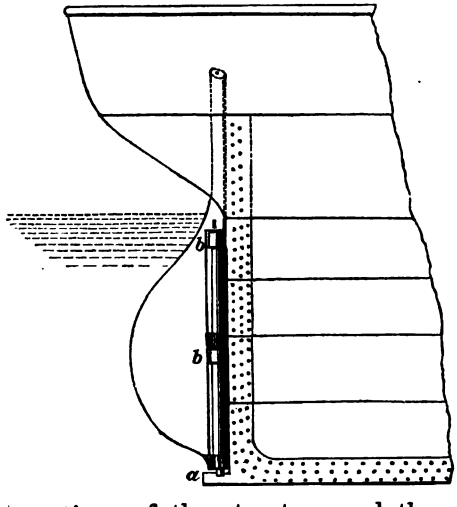
$$W=\frac{4M}{l}=\frac{4 s_1 I_0}{h_1 l}=\frac{4\times 20\times 215348}{14\times 240}=5127 \text{ tons.}$$

$$\text{or, } \frac{4 s I_0}{h l}=\frac{4\times 18\times 21534}{21\times 240}=3076 \text{ tons.}$$

When the top is yielding by this load, viz., 3076 tons, with 18 tons per square inch, the bottom section would undergo only about 12 tons.

This deficiency is to some extent made up in practice by the wooden deck, which acts to some extent in its resistance to tension, and considerably more in its resistance to compression, and the breaking strain may therefore be taken at 4000 or 8000 tons equally distributed.

Fig. 81.




The other portions of the structure and the union of the plating to the stern-post and cutwater at the bow and stern

Digitized by Google

respectively, are entitled to consideration. In the construction of an iron ship it is necessary to have an iron stern-post, to which the sheathing plates and rudder are attached. In most cases they are of the form shown in fig. 81, and consist of a large forging recessed to receive the ends of the plates—double-riveted—and the thimbles or sockets in which the rudder revolves, as shown at *a* and *b b*. At the bottom the post terminates in a strong forging prepared to receive the foot of the rudder, and to unite at the same time with the bottom plates, which are thickened under the centre keelson; and as there is no keel, this forging and the plate must be firmly secured by rivets forming the junction of the stern-post and the bottom sheathing of the ship. The same method of construction may be observed in the union of the hull with the cutwater, which being similar to that of the stern-post, renders further description unnecessary.

The foregoing remarks are directed almost exclusively to sailing-vessels, or what are called clippers, carrying passengers and goods. Those intended for steamers with screw-propellers would be nearly of the same build, but differently prepared at the stern for the reception of the screw, where a double and more elaborate forging would be required, and other local conditions, well known to the engineer and builder, and which, therefore, we need not attempt to describe. The same observations will apply to paddle-wheel steamers, and the same principle of construction also applies, in so far as it relates, to the hull, and the distribution of the material.

3. Having thus investigated what may be considered the best principle of construction for iron vessels of a mercantile character, we now come to the more important question of *Ships of War*, which, owing to other causes besides those of seagoing properties and strength, require careful consideration.

When we consider the purposes to which vessels of war may be applied, and the resistances they have to encounter, to say nothing of the many conveniences that are required for lodging some hundreds of men in a small space, and that room must be provided for steam-engines, boilers, and coals; that the vessel must carry heavy guns and some hundreds of tons of armour-plates bolted to her sides; that she must have a beak

Digitized by Google

of enormous strength, calculated to run down and sink an enemy's ship; moreover, that she must be swift for the chase, and equally alert in making her escape when overpowered by a superior force—we have some idea of a modern ship of war. Now, to construct a ship with all these qualifications and conveniences is the duty of the builder, and although the means are at hand, with the knowledge and skill of the Controller and the Lords Commissioners of the Admiralty, yet it is nevertheless an arduous and responsible duty which both parties are called upon to perform.

On this important subject it may be assumed, that a *landsman* is not the proper person to direct constructions of this kind, nor would it be prudent for us to enter upon the task, if it were not well known that a musician is not the person to make the instrument on which he plays, nor is the mariner who navigates the vessel, the only one calculated to design and build the ship. On the contrary, these duties devolve upon those who are neither musicians nor seamen, but who are notwithstanding better prepared for the task from their education, knowledge, and long experience in the use of wood and iron in its application to these constructions. It is sufficient for the sailor to navigate and fight the ship, without burdening him with the laws of construction, and to leave to other hands the duty of providing suitable vessels on which the safety and the honour of his country depends. What is therefore wanted is proper and suitable vessels, and we may rest assured there will be no want of skill in their management nor lack of courage in the fight when duty calls upon the officers and crews of Her Majesty's Navy to assert and maintain the honour of the British flag.

It has been noticed that ships of war, having the same seas to navigate and greater risks to encounter than merchant vessels, should be made proportionately stronger than those intended for a different service, and the construction of iron ships calculated for the purposes of war present other considerations besides those which are required in building vessels exclusively commercial. They may be thus considered:—

1st. Their tonnage or magnitude.

2ndly. General principles of construction.

Digitized by Google

3rdly. Ironclads such as the 'Bellerophon' and 'Warrior.'

Lastly. The American system of construction.

These are the subjects which we propose to discuss, and taking into account the numerous points which have to be considered, we must leave to other and more experienced hands an immense amount of detail with which we are unacquainted, and which necessarily must be omitted. In the leading features of the construction we may, however, be enabled to offer some useful suggestions; and taking them in the order given above, we have to treat of—

1st. *The Magnitude or Tonnage of Ships of War.*—This is a question of deep importance to the country, and doubtless it has received careful attention on the part of Her Majesty's Government. Since the first introduction of plated armour-vessels, many changes and many improvements have been effected both as regards the manufacture of the plates and the guns to which they offer resistance. For a long time these antagonistic forces were nearly balanced; but as the plates were thickened and improved, the guns were strengthened and enlarged, until it was found that guns could be made to perforate plates much thicker than a ship of ordinary size could carry. As much as 6, 8, and even 10 inches thickness of plate have been perforated and smashed by guns of large calibre, throwing bolts and shot varying from 300 to 600 lbs. in weight, and which, with increased charges of powder, would pierce much greater thicknesses of plates than our largest ships are calculated to support. This was the state of the enquiry when the Iron Plate Committee left off their labours, and it has now to be considered what description of iron, what weight and thickness of plates should be introduced, and how distributed, to resist these formidable weapons of attack.

It has been suggested and strongly recommended that our ships of war should be greatly enlarged, in order to carry armour-plates of any required thickness; but we have had some experience in the unmanageable nature of large ships in the case of the 'Great Eastern,' and it appears from all previous experience that the smaller description of vessels, from 2,000 to 2,500 tons burden, are infinitely more active and sufficiently large to carry armour-plates as a protection from the shot of powerful guns,

Digitized by Google

unless in the case of boarding or at close quarters, when a breach may be expected on both sides. At a thousand or fifteen hundred yards, armour-plates from 5 to 6 inches thick would, in our opinion, be too much for the guns, and would act as a powerful auxiliary to the safety of the ship.

In the absence of actual practice, or experimental data, to guide us in reference to the dimensions or tonnage of ships of war, we may be justified in selecting for illustration between the two extremes, exclusive of gunboats, a vessel of 2,000 to 6,000 tons burden, or one of 4,000 tons. In this selection we have a good-sized vessel, calculated to carry armour plates from 5 to 6 inches thick, placed at the most vulnerable parts of the ship. A vessel of this size, with double engines and screws, would meet, as regards dimensions, nearly all the requirements of the service. Such a vessel, armed with heavy guns, four of them worked in the line of the keel at the bow and stern, and the remainder (eight or ten in number) as a broadside battery, would, in our opinion, be a match for the heaviest vessel afloat.

Let us examine how such a vessel would work—how she should be armed, plated, and made as far as possible bomb and shot-proof. If we suppose her armament to be 12 guns,—two at the bows, and two at the stern, including eight of the same weight—350-pounders—at midships,—we have a vessel capable of delivering a double broadside of 2,800 lbs., including 800 lbs. from the bows and 700 lbs. from the stern, making a total of 4,300 lbs.; nearly one-half of this might be fired at once, if in action with one or more of an enemy's ships.

To render a vessel of this kind shot-proof would require her to be clad with thicker plates than she was able to carry; but adopting a partial form of plating, so as to give security to the vessel in the first instance, and protect the men at the guns in the second, she would require to be covered with plates 6 inches thick at midships, and gradually to taper to 4 inches at the stem and stern—this covering to extend 4 feet below and 2 to 3 feet above the water-line, making a belt of 6 feet 6 inches or 7 feet in width all round the ship immediately below the lower deck. On this principle the ship, in most cases, would be securely protected in a general engagement. As respects the bottom and the men at the guns, it is doubtless desirable that both



Digitized by Google

should be protected; but as that cannot be done without overloading the ship with an enormous dead-weight, it is proposed to construct shields—one near the bows, as at A, figs. 82

Fig. 82.

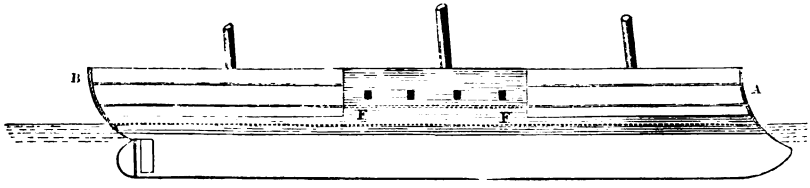
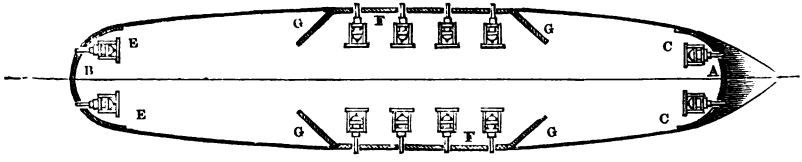



Fig. 83.




and 83; another lighter one, B, at the stern; and one on each side, as F F. The bow and midship shields to be 5-inch thick plates, and the one at the stern only 3½-inch. On this principle the intermediate spaces would have no protection, the armour-plating being entirely dispensed with in order to lighten the ship.* This modified form of armour-plating is the more important, as it enables vessels of light tonnage to be securely built and protected, not only in the more vulnerable parts, at the midship batteries, but the fore and aft guns would also be protected by iron screens, as shown at A and B in figs. 82 and 83. On this principle the two guns at the bows would be protected by armour-plates 5 inches thick at A, and tapering to 4 inches at C C. The same would be observed at the stern, only that the plates in this case would be 4 inches thick at B, and 3 inches at E E. The midship battery would be protected by 5-inch plates at the sides F F, and 4½-inch turned round the corners

* Since these views were penned we have been favoured with a section of the 'Penelope,' of nearly 3,000 tons burden, which embodies all the means of security with improvements contained in the foregoing remarks. This vessel is admirably adapted for securing not only safety to the ship, but protection to the men at the guns. (See page 211.)

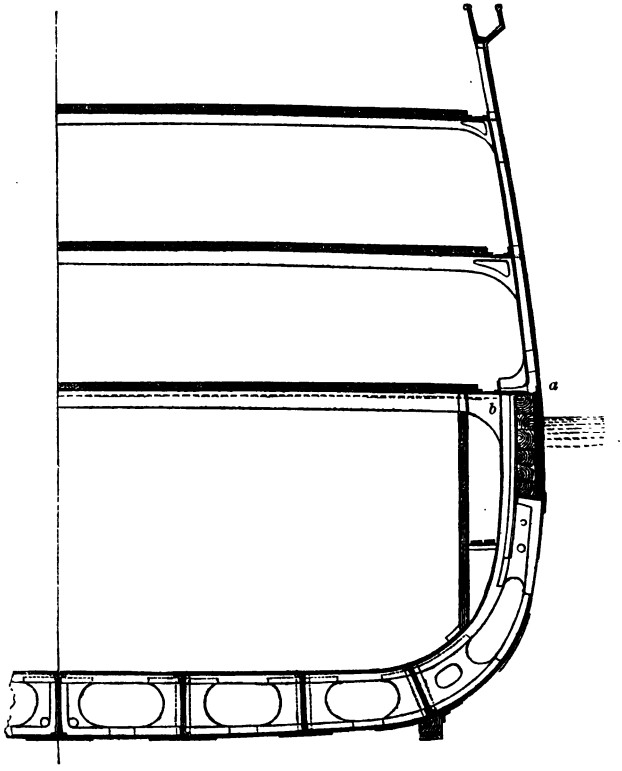
Digitized by Google

G G G G, for the purpose of throwing off a stray shot fired in an oblique direction. This construction appears to approximate to what is wanted for vessels of this class; and in going into the calculations of weights, displacements, &c., it would appear that such a vessel would not be overburdened with weight, but would nearly meet all the requirements of security and speed.

2*ndly*. *General Principles of Construction.*—The views we entertain of the construction of ships of war have been to a great extent verified in the 'Penelope.' This vessel is an improvement

Fig. 84.

'Penelope.'




on the 'Bellerophon,' as a considerable part of the weight of the iron armour-plates has been dispensed with on the principle recommended in the foregoing statements. The 'Penelope' is



Digitized by Google

also a convenient and moderately-sized vessel, carrying eight broadside guns of large calibre at midships, with two more guns at the bows and two at the stern.

The peculiar properties of this vessel are that she is surrounded with a belt of armour-plate 6 inches thick to a depth of 4 feet under the water-line, and 18 inches above, terminating (as may be seen in the section, fig. 84) at the height of the top of the lower deck, *a*. The 6-inch plates will be carried along each side with the teakwood backing placed against the skin and frames of the ship, as represented in section at *b*. Thus the vessel will be securely protected under the water-line, probably with a diminished thickness of the plating as it approaches the bow and the stern. The protection of the men at the guns has not been lost sight of in the construction of the 'Penelope,' as the guns at midships are surrounded with armour-plates 5 inches thick; and what appears to be a great improvement is, that the four midship guns next the bows and stern can be fired as broadsiders or at right-angles to the line of the keel, or they may be discharged through the portholes (B B B B, fig. 86) at an angle of 15° with the line of the keel. This arrangement with her four heavy guns would enable the vessel to command an enemy's ship bearing down upon her for attack, or she might use the same number of guns and the same weight of metal in either direction in conjunction with or independent of those at the bows and stern. In this case the 'Penelope,' if armed with 400-pounder guns, could fire a broadside of 1,600 lbs., or she could discharge the same weight in the direction of the bow or the stern.

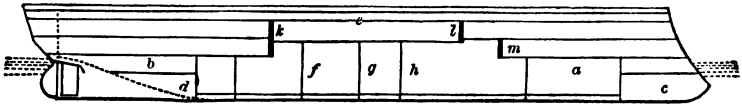
The 'Penelope' appears to be one of the best-designed vessels yet introduced into the service. She embodies all the elements of security as regards the safety of the ship, and—provided her armour-plating which surrounds the midship battery is sufficient to keep out shell and shot, and not too heavy so as to affect her steaming and sailing powers—we may safely congratulate the Admiralty on having attained a desideratum in the application of iron and the construction of a sound and—as far as that is possible—nearly a perfect ship.

The following diagrams show the interior dimensions and arrangements of this vessel. Fig. 85 is an outline of the longi-

Digitized by Google

tudinal section, and fig. 86 is a plan showing the midship battery and the position of the guns. In fig. 85 it will be observed that the fore and aft decks are covered at *a* and *b* with ½-inch plates, and immediately under are watertight compartments, *c d*; and in the whole length of the ship there are seven

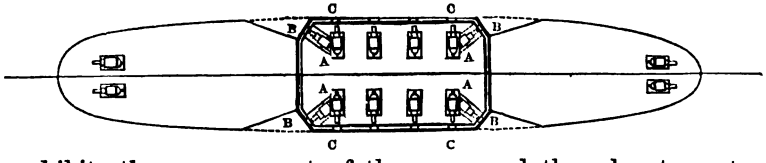
Fig. 85.
'Penelope.'




bulkheads, three of them watertight from the outer skin of the hull up to the lower deck. At the points *f g h* are three more bulkheads with transverse armour-plates *k l m* to protect the battery, the steam-engines, and the boilers from being raked by a longitudinal fire, and the upper deck, *e*, is entirely covered with steel plate $\frac{5}{16}$ inch thick.

Fig. 86 is a simple plan of the main or fighting deck. It

Fig. 86.
'Penelope.'




exhibits the arrangement of the guns, and the advantages to be gained in having the power to fire the four guns, A A A A, either as broadsides or as assistants to those at the bows and stern.

In this construction it will be seen that the spaces B B B B are left entirely open, in order that the guns may be fired in those directions, or through the portholes C C C C, as circumstances may require.

We now come to the 'Bellerophon,' an armour-plated vessel which appears to meet the requirements of the service as a powerful and a handy ship; she is of medium size, strongly built, and well protected by armour-plates, and may therefore be considered a useful vessel. As the 'Bellerophon' was the first

Digitized by Google

vessel of war built on the new principle of double bottom and longitudinal cells, a full and detailed description of her construction may be interesting in exhibiting this important principle.

The 'Bellerophon' being the first ship built upon what we consider sound principles, we deem it important to show in detail how the different parts are united, so as to form in combination a strong and effective ship. We may however observe, *en passant*, that great credit is due to the Naval Constructor for having freed himself from all preconceived opinions, and for having adopted every improvement and every recommendation calculated to increase the efficiency and durability of this novel construction, and to promote the transfer, now in progress in the Navy, from wood to iron. It is difficult for mankind after a certain age to divest themselves of opinions which in the early stages of their professional career they were taught to believe were the only true principles on which they could practice and exercise their skill. Doubtless an adhesion to these principles, as far as they go, is commendable, but the progress of science and the adoption of an entirely new material of construction introduces new laws and new principles, widely different from those previously in use. It is not therefore surprising that new constructions and new material should require new heads and hands to carry out measures calculated to set aside old customs, and supplant them with entirely new and more important structures. Young men enter upon the stage of life with new ideas and readily adopt the practice of new principles. They grow up with the changes in progress, present to the world new ideas and new conceptions in unison with those which the progress of science suggest. It is in this way that persons like ourselves are superseded in actual practice by younger and more vigorous intellects, free from prejudice, and therefore better able to meet the requirements of the age. We have ventured upon these remarks to show that in the case of the 'Bellerophon' the Admiralty are fully aware of the necessity of the changes now in progress, and are justified in calling to their aid a class of men conversant with iron constructions, and free to adopt and to apply every known principle calculated to improve and complete the efficiency of Her Majesty's Navy.

Digitized by Google

The 'Bellerophon' is a medium-sized vessel, about 300 feet long, 56 feet beam, and measures 4,216 tons burden. She is constructed entirely of iron, with lower, middle, and spar or upper decks. She carries a midship battery of eight large guns, with two 400-pounders at the bow, and two 300-pounders at the stern. She is covered with armour-plates 6 inches thick all round to a height of 15 feet above and 5 feet below the water-line. At midships the armour-plating is continued upwards to the spar-deck, and completely covers the guns on each side. The outer parts are not shielded, but left with no other protection than the sides and two enormous bulkheads at the midship battery.

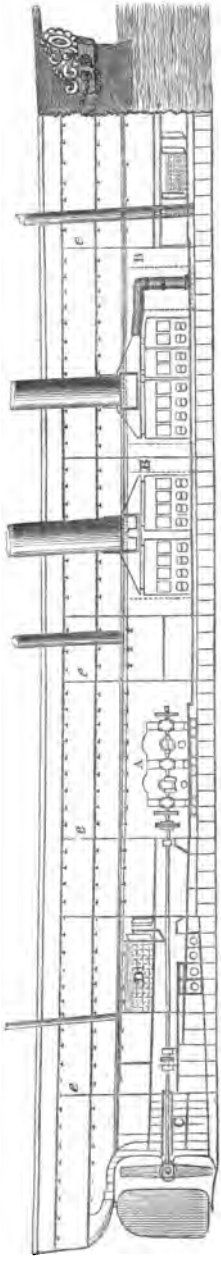


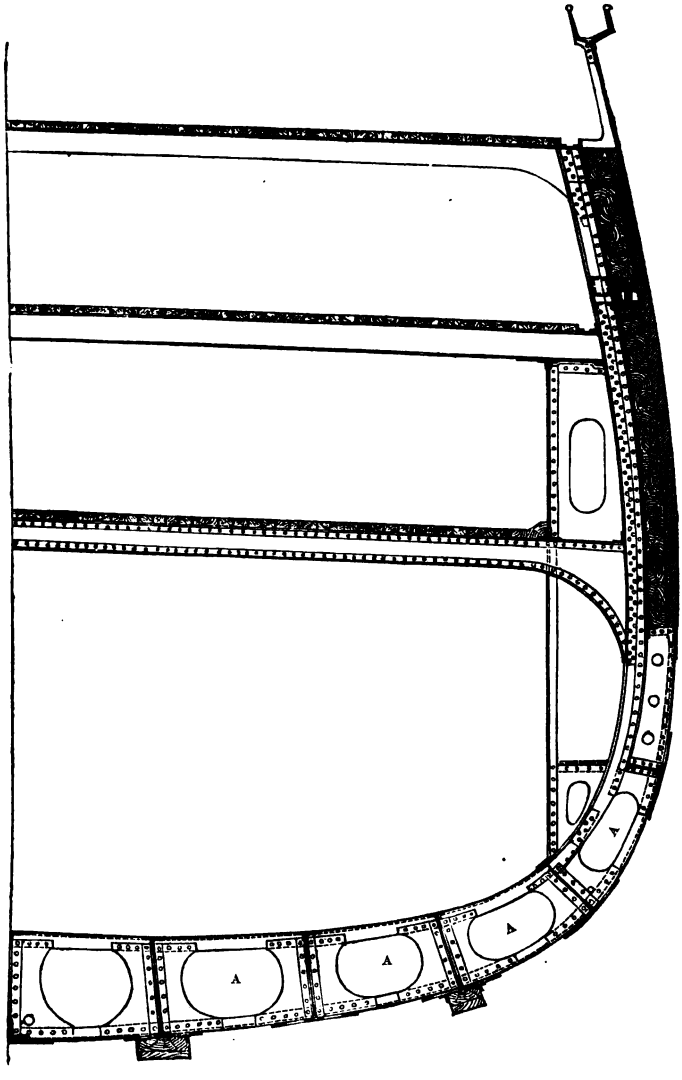
Fig. 87.—'Bellerophon.'—Longitudinal Section.

Fig. 87 represents a longitudinal section of the 'Bellerophon,' showing the position of the engines, boilers, bulkheads, &c. In this it will be observed that the engines, boilers, &c. occupy the spaces A B B, and are fixed upon cross-beams attached to the keelson under the lower deck; C is the watertight tube for the propeller-shaft, and D the space occupied by the after-magazine and water-tanks. Under these are the thrust chock-bearers and iron box-bearers, supporting the line of the propeller-shaft. In the divisions of this vessel there are four watertight compartments, *e e e e*, divided by iron bulkheads, and others that could be made watertight if necessary—the first extending from the bottom to the underside of the fighting deck, and the others to the lower deck. Immediately

Digitized by Google

behind the magazine is the mizenmast, between the engines and the boilers the mainmast; and the foremast is also close to the fore-magazine, thus distributing the weight so as to trim the ship.

Fig. 88.
'Bellerophon.'—Midship Section.




Digitized by Google

Fig. 88 (p. 216) represents a half-transverse section of the 'Bellerophon' at midships, in which is exhibited sections of the longitudinal cells, A A A A &c., and the principle of construction for the double bottom. In this sketch it will be seen that there are eight cells about 6 feet wide, and varying from 4 feet to 3 feet 4 inches deep on each side of the centre keelson. Each of the keelsons is composed of $\frac{3}{8}$-inch thick plates, extending the whole length of the vessel to the point of convergence, where they respectively run into each other, and terminate on the centre keelson, B, which connects with the stern-post and cutwater, and represents the keel. Figs. 89 and 90 show sections of the construction of one of those cells, and of which the following is a description.

Fig. 89 is a longitudinal section showing the joint of the midfeather of one of the keelsons at *f*, chain-riveted with two $\frac{5}{16}$-inch thick covering plates, one on each side, in order to resist

Fig. 89.

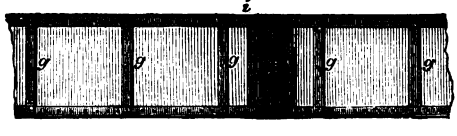
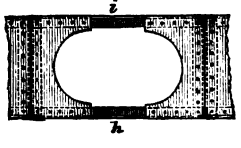



Fig. 90.




tension, and the cross-ribs *g g g*, which form the cells and constitute the frames of the ship. Each of the keelson-plates is $\frac{3}{8}$ths of an inch thick, and is riveted with double angle irons to the outer skin, *h*, and the iron plates, *i i*, which form the double bottoms. Transversely the same principle of construction is pursued with double angle irons to receive the gussets or stiffening plates, which are securely riveted to the angle irons of the floor-plates and the outer sheathing. This gives great stiffness to the bottom as also to the iron flooring above, and these, with the watertight bulkheads, offer the necessary security against accident to the outer skin and frames of the ship. As respects the plating or outer skin of the ship, each of the transverse joints are treble-riveted, the same as the keelson-plates, on the chain-principle; and were it not for the wear and tear to which the hull is subject, the thickness of these plates

Digitized by Google

might be reduced from $\frac{1}{10}$ to $\frac{1}{8}$ of an inch less than what is represented on the section at fig. 88, which gives the correct proportions of this portion of the structure.

As respects the decks, the upper deck is covered all over with $\frac{1}{2}$-inch steel plates, and the main deck with iron plates of the same thickness. To these are added stringers of thicker plates and angle irons along the decks on each side, and, taking into account the strength of the sides, teak—backing, and armour-plates at midships, we may safely apply the formula $W = \frac{a\,d\,c}{l}$ which gives the strength of the vessel, when treated as a hollow girder supported on two points at the ends. In this case, we have where

$W$ represents the breaking weight in tons,
$a$ area of the top or bottom section = 670 inches,
$d$ the depth = 32 feet,
$l$ the length = 260 feet,
c the constant = 60,
Hence

$$W = \frac{670 \times 32 \times 60}{260} = 4947{\cdot}6 \text{ tons},$$

the breaking weight in the middle, or 9895·2 tons, equally distributed throughout the whole length of the vessel.

We have now arrived at the point where it may be necessary to notice one of the first iron vessels in Her Majesty's Navy, built for the purpose of receiving armour-plates $4\frac{1}{2}$ to 5 inches thick, and calculated at that time to be invulnerable to the heaviest guns—the 68-pounders—then in use.

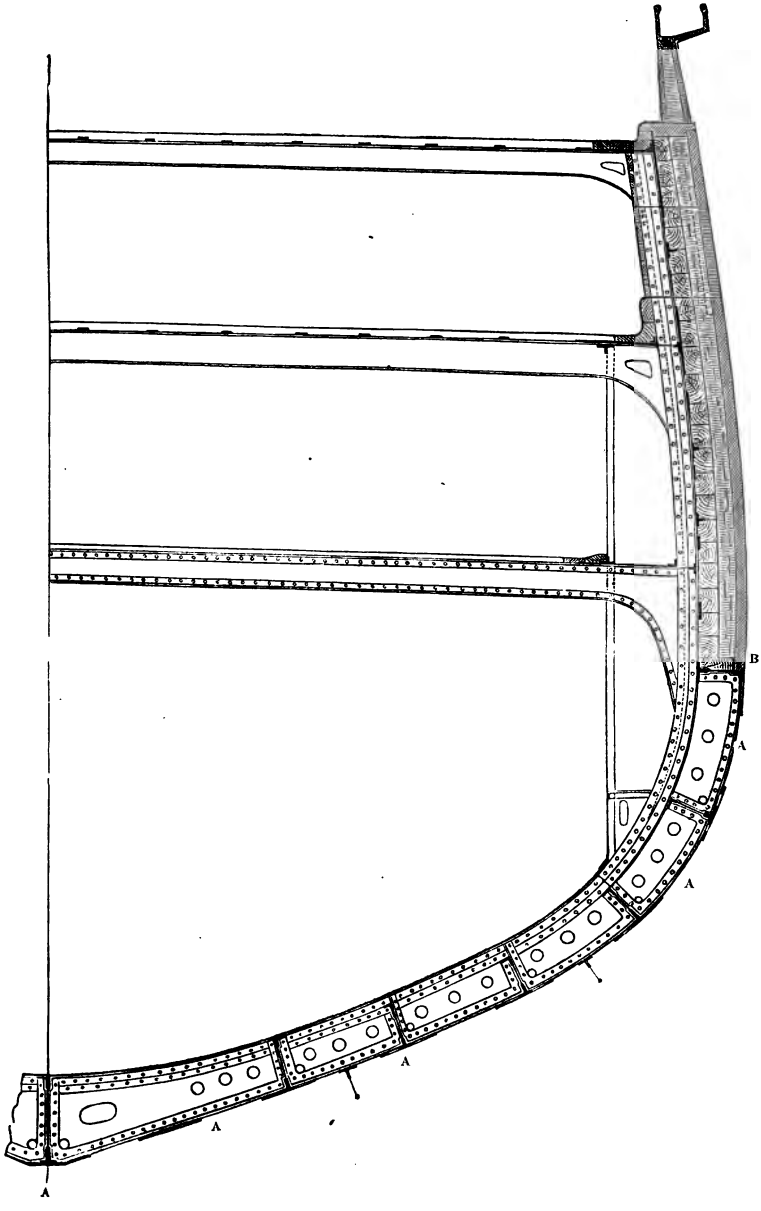
This vessel, the 'Warrior,' and her sister ship the 'Black Prince' —of precisely the same construction, shape, and power—were carefully considered and well designed to meet all the requirements of an antagonistic force from an armament such as above described. Time and experience, however, have shown that the 68-pounder, although a formidable gun, is far short of the damaging power that has since been attained; and the experiments at Shoeburyness on the 'Warrior' and other targets clearly exhibited that something more was wanted than $4\frac{1}{2}$-inch thick plates, with 18 inches of oak and teak backing, to keep out

Digitized by Google

shot from rifled guns at short range. Mr. Whitworth was the first to demonstrate these facts, and to show that $4\frac{1}{2}$-inch plates

Fig. 91.

'Warrior.'—Midship Section.




Digitized by Google

on the 'Trusty' were no match for his steel bolts, which went through the plates, and which with a few more rounds would have sunk the ship. These and other subsequent experiments showed the weak points in the build of the 'Warrior' class, and suggested new appliances and new constructions, such as we have endeavoured to describe.

The 'Warrior' and 'Black Prince' (of the first of which we give an engraving in the frontispiece) are, nevertheless, noble vessels, well protected with armour-plates to a depth of 6 feet under the line of floatage, and for about one-third of their lengths have a certain portion of the bow and stern unprotected and open to the enemy's shot. The whole of the sides are, however, well secured with 4½-inch armour-plates, with 18 to 20 inches thick of teak and oak backing, and if to these be added two transverse armour-plated bulkheads, we have some idea of the security which those vessels afford when encountered by a vessel of equal or of superior force.

As regards the build of these vessels, they do not contain the elementary strength of the 'Bellerophon,' as exhibited in the longitudinal keelson and cellular form of construction. They are, however, well and securely built, with a partially constructed double bottom, and longitudinal frames and transverse ribs, as shown in section, at A A A A, fig. 91. These frames are of no great depth, but they add to the strength and stiffening of the angle iron of the transverse ribs, being united by a solid plate from the centre keelson, A, round the bilge to the bottom of the armour-plating at B, which renders that part of the structure of greatly increased strength.

The decks are covered with iron plates, which, to a certain extent, answer the purpose of stringers, but they are defective in those parts, both as regards the tensile and compressive powers of resistance, and are inferior in strength to the corresponding parts in the 'Bellerophon.'

These were the first ironclad vessels of any great magnitude which made their appearance as ships of war, and considering that they were built previous to the experiments on armour plates that have since been made, they approximate closely to the construction of those founded upon more certain data.

Notwithstanding what has been said on the build of iron-

Digitized by Google

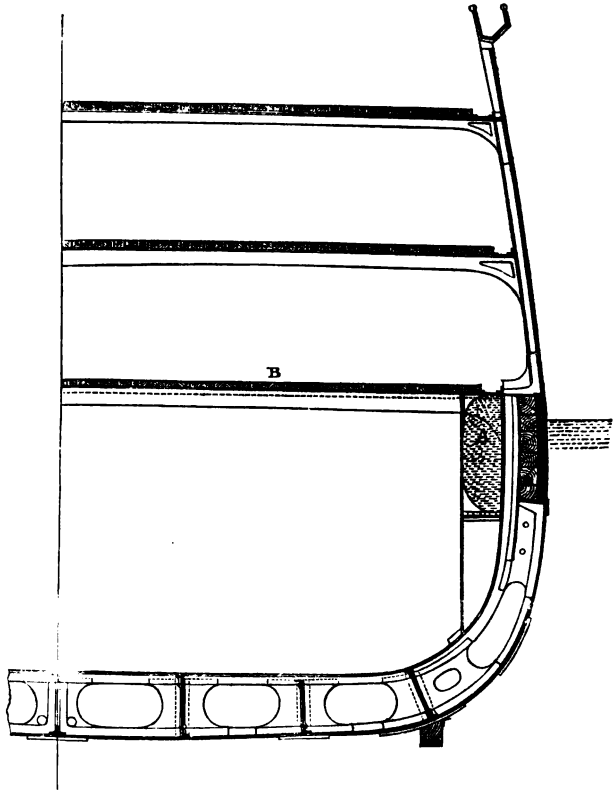
plated vessels, and their limited powers of resistance to guns of large calibre, it is evident, from the experiments to which we have referred, that the question of security against shot and shell is one of great importance. There cannot exist a doubt that vessels can be built large enough to carry armour-plates 10 inches thick, but it remains to be seen whether such vessels would or would not be almost totally unmanageable in action; and we have yet to learn to what extent it would be prudent to build such monster ships, and embark the public money in speculations where the principles on which they are founded are not fully developed. We have already noticed the dangerous nature of armour-plates when perforated and driven through the backing into the interior, making a large and dangerous breach in the side of the ship. With such heavy ordnance to contend against, it is a question whether, in so far as regards the officers and crew at close quarters, the loss of killed and wounded would not be greater with than without the armour-plates. In this latter case they would only be exposed to the shot and the splinters from the sides or bulwarks of the ship; whilst, on the other hand, in the case of the armour-plates they would not only be exposed to the entrance of shot and shell, but to large fragments of iron driven forward, with the most deadly effect to those who happen to be in the way of the range of these destructive missiles. This is one of the reasons why we advocate a clear deck and plenty of room for an active crew to work the guns. Open ships entirely free from obstruction and no harbour for skulking is what the British sailor requires, and what he would infinitely prefer to the imperfect shelter of armour-plates. He would then strip to his work, fight with greater courage, and being sure of his ship with thick plates, as we have recommended, along the water-line, his only object would be to disable his adversary and give a satisfactory account of the enemy.

If this system, of simply protecting the ship by a belt of armour along the water-line with free and open decks, applies to the case of vessels where the batteries are concentrated amidships, the same principle will also apply to the turret plan. It is well known that the great advantage of the turrets consists in the power to revolve and work the guns; but this does not compensate for the crowded state of the interior, and the

Digitized by Google

accidents that may occur in driving in large pieces of armour-plates and backing, to the discomfort of the inmates and, in all probability, the destruction of both men and guns. These are difficulties which require consideration; and till such time as we have further experience, these and other suggestions will require to remain in abeyance for further development. In the interim, we have to recommend attention to the foregoing

Fig. 92.




principles of construction, which we have endeavoured to urge on the attention of the Government; and as most of them are founded on experimental research, we have the greater confidence in their development for the increased security and benefit of the British Navy.

4. Before closing this part of the subject, it may be desirable

Digitized by Google

to direct attention to what we are unable, in the absence of experiment, confidently to recommend. It is, however, of some importance to ascertain what would be the effect of a water-shield running parallel with the armour-plating all round the ship, from the line of floatage to a depth of 4 feet under that point, as exhibited in the section, fig. 92, at A. The object of this construction would be to receive any accidental shot that strikes the vessel with a force that would penetrate the armour-plates, the backing, and the skin of the ship. In the event of such an accident, it appears obvious that water, which presents a powerful resistance to the entrance of bodies at high velocities, would be an element into which a spent shot at greatly reduced velocity might come to a state of rest. If we are correct in these views the vessel would require to be built with the double bottom carried up to the lower deck, B; and from that point to a depth of 4 feet, the sides would be enlarged to the dimensions shown in the section. Should this arrangement be found advantageous, it would not be necessary to retain the tank full of water excepting only in the time of action, and that for the exclusive purpose of preventing the entrance of shot into the interior below deck, and thus to render the vessel what is considered unsinkable under every condition of attack or defence.

Next to water, sand is the most powerfully-resisting medium, but it is unsuitable for such a purpose on account of its weight; and as the water-space can be filled and emptied at pleasure, it is probably in more respects than one preferable to that of sand or any other solid lining. We hope the time is not far distant when we may be able to prove the efficacy of these views by a series of experiments calculated either to confirm or abandon this principle of protection.

5. The limits of this work will not admit of an extended description of the different armour-plated vessels of war as designed for this and other maritime nations: it may, however, be convenient to give the dimensions, tonnage, armaments, and other conditions of some of the leading vessels of the ironclad fleet. For this purpose we have selected and tabulated ten vessels; from which it will be seen that, with three exceptions only, most of the vessels are of large tonnage, and some of them carrying heavy guns.

Digitized by Google

TABLE I.—SHOWING THE SIZE, TONNAGE, ARMAMENT, &C. OF SOME OF THE ARMOUR-PLATED VESSELS OF HER MAJESTY'S NAVY.

| Name of Vessel | Length | Beam | Tonnage | Draught of Water | Thickness of Armour Plate | Description of Armament | Weight of Broadside | Calculated Speed |
|---|---|---|---|---|---|---|---|---|
| | feet | ft. in. | | ft. in. | ins. | | lbs. | kts. fur. |
| Defence . . | 280 | 54 2 | 3,720 | 25 6 | 4½ | 5 68-pounders and 2 110-pounders | 560 | 11 3 |
| Prince Albert . | 240 | 48 0 | 2,529 | 20 0 | 4½ | 3 300-pounders and 2 100-pounders | 1,120 | 11 4 |
| Valiant . . | 280 | 56 3 | 4,063 | 25 2 | 4½ | 12 68-pounders and 3 100-pounders | 1,256 | 11 75 |
| Warrior . . | 380 | 58 0 | 6,109 | 26 2 | 4½ | 13 68-pounders | 884 | 14 3 |
| Achilles . . | 380 | 58 3 | 6,079 | 26 2 | 4½ | 13 68-pounders | 884 | 14 1 |
| Minotaur . . | 400 | 59 3 | 6,621 | 26 2 | 5½ | 13 68-pounders and 4 110-pounders | 1,324 | 14 3 |
| Royal Oak . | 273 | 58 5 | 4,045 | 26 7 | 4½ | 12 68-pounders and 4 110-pounders | 1,256 | 11 5 |
| Favorite . . | 225 | 46 9 | 2,186 | 21 11 | 4½ | 2 68-pounders and 2 110-pounders | 356 | 10 8 |
| Enterprise. . | 180 | 36 0 | 990 | 15 6 | 4½ | 2 110-pounders | 136 | 9 5 |
| Royal Sovereign | 240 | 62 0 | 3,963 | 28 6 | 4½ | 5 300-pounders | 1,500 | 12 2 |

Digitized by Google

It might have been desirable to have given a complete list of the ironclad fleet of Great Britain: the object of this work is not, however, the Statistics of the Navy, but the principle on which Iron Vessels of War should—according to our views—be built and armed. In this attempt we have probably not succeeded to the desired extent, as there are many points of construction not touched upon, and many technicalities with which we are not acquainted. We, however, venture to hope that this inquiry will not be found altogether barren of information, but of that description calculated to lead the Iron Ship Builder and Naval Architect to a system of construction founded on the principles of unerring and definite laws.



Digitized by Google

## CHAPTER XII.

### ON THE PRACTICAL CONSTRUCTION OF IRON SHIPS (CONTINUED).

1. HAVING from experimental data, as regards construction, arrived at certain conclusions of a definite character, it may be interesting, before we close this part of our subject, to direct attention to what has been done by the Americans during the eventful war which has for the last four years devastated that country. It may easily be conceived that an ingenious and enterprising people like the Americans would not be behind in the improvement and construction of ironclad ships, and we are fortunate in having before us several drawings and specimens of the ironclad vessel that took the most active part in the naval engagements during the war. We have already noticed what has been done and what may yet be accomplished in that way; and it may be interesting to give a few examples for the information of those interested in such matters.

2. We have before us sections of the new ironclad frigate 'New Ironsides,' built entirely of wood with sloping sides (A, fig. 93, p. 227), and a flat bottom as shown at B. This vessel is very shallow when we compare the width of beam, 56 feet, with the depth, which is only 28 feet. She is covered with 5-inch plates, to a depth of 3 feet 9 inches under the load line, and another line of plates under 4 inches or about $3\frac{3}{4}$ inches thick to a further depth of 2 feet 6 inches, making the whole depth of plating under water, when the vessel is loaded, 6 feet 3 inches. Draught of water, 16 feet.

We are not in possession of the length, engine-power, and other details of this vessel, but, assuming that a heavy armament is necessary, her maximum speed could not exceed 7 knots an hour. She does not appear to be intended for turrets, and

Digitized by Google

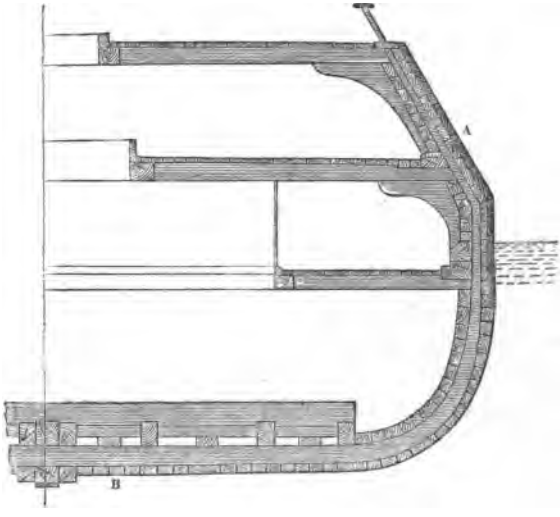
Digitized by Google

Digitized by Google

would therefore be pierced through the sloping sides at A, for broadside guns, with two or four more at the bows and stern. This would probably be the equipment of this vessel, and, considering her great width of beam and flat bottom, great speed

Fig. 93.

'New Ironsides.'—Midship Section.




could not be expected. The danger in this and all other wooden vessels would be from the effects of shells; and although we have endeavoured to secure vessels, whether of wood or iron, from being sunk by the entrance of water, we have no security from live shells making their way through armour-plates into the body of the ship. These appear to us considerations which require attention, and nothing seems so well calculated to guard against both elements—fire and water—as iron.

3. The Americans are a very singular and a very clever people, full of ingenuity and contrivances to meet the demands of the moment, and availing themselves of every improvement that happens to touch upon the question before them. This will be seen to be the case in the instance of the turret-vessel 'Chickasaw,' built for two turrets AA, fig. 94, each pierced for two guns about one-third from the bow and the same distance from the stern. This vessel, evidently intended for a river-boat, is



Digitized by Google

230 feet long, 56 feet broad, 10 feet deep from the top of the deck to the bottom of the keel, it has one deck, and is only 10 or 12 inches above the water-line, as shown in fig. 94, taken from a photograph sent over from America to this country. From the construction of this vessel it will be noticed that she has a perfectly clear deck, with simple stanchions and iron rods instead of bulwarks. This gives abundant space for the working of the turret and guns; what armour-plating there is will be found upon the turrets, and to a depth of a few feet along the sides and round the bows under the water-line. Her draught of water is only 6 feet 6 inches.

4. The same construction is observed in one of the most complete light-draught monitor class, the 'Nauset,' built by Mr. Donald McKay, Boston, Massachusetts, U.S. This vessel (figs. 95 and 96) is 223 feet long, 44 feet 3 inches beam, with one deck, and only 8 feet 6 inches deep from the top of the deck at midships—which is well rounded and composed entirely of large balks—to the bottom of the hold. She is of a very peculiar construction, iron-built, and protected all round the sides and ends with a coating of hard timber 3 feet 8 inches thick at midships, increasing to 5 feet thick at the boilers and engine room, as shown in section at A A, figs. 97 and 98. There is only one turret, which is covered with iron armour-plates 10 inches thick, and the remainder of the vessel depends on the thickness of the timber casing and a belt of armour $3\frac{1}{2}$ inches thick as a protection to the skin of the ship. This belt of armour is composed of three or four plates bolted together, and extends for a distance of 1 foot 3 inches above and 1 foot 8 inches below the water-line. Between the wood-casing A A and the skin of the ship is a space, B B B (figs. 97 and 98) of about 2 feet wide, formed of plates as an outer sheathing to receive the timber and to admit a line of pipes, *c c c*, through which pass currents of air for the purposes of ventilation. These pipes are supplied with air from two fans, worked—as appears from the drawing—with two separate pairs of oscillating engines, *e e*, figs. 95 and 96; and in the line of the pipes on each side of the vessel proper valves are introduced at regular distances to supply each compartment with fresh air: and it is also more than probable that steam can be introduced for the purpose of heating in cold

Digitized by Google

Digitized by Google

Digitized by Google

weather. There are also two large fans, D D, under the turret, worked by separate engines; and these to all appearance are intended to pour volumes of air into the furnace to excite combustion, and thereby increase the supply of steam to the engines. There are also two propellers, with an engine, *g g*, to each for the purpose of training; and in order to facilitate that object and assist the screw-propeller, a broad fan-rudder, E, is attached.

Fig. 97.
'Nauset.'—Section through Turret.

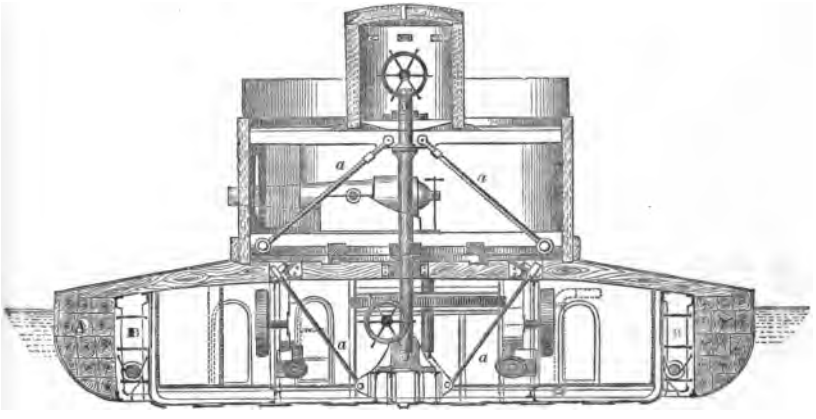
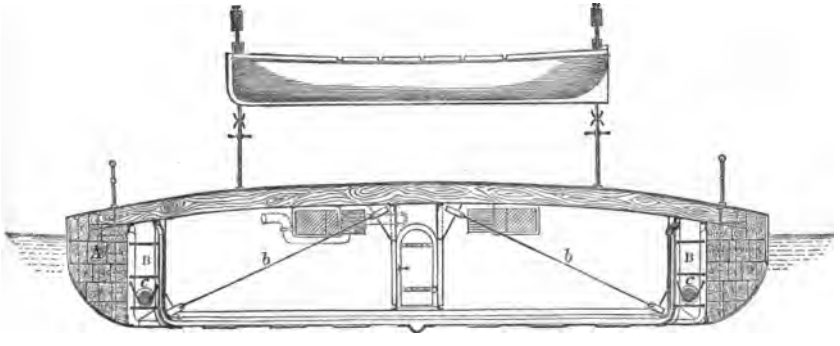



Fig. 98.
'Nauset.'—Midship Section.




The architect or builder has studied every possible convenience in the design of this vessel, and has left nothing short of making all the movements as nearly as possible self-acting. For this object, the revolving of the turret is attained by a separate

Digitized by Google

donkey-engine, *h*, in the same way as the fanners and other machinery for propelling the ship.

As respects the accommodation for the officers and crew, every consideration has been given for convenience in a limited space. The berths and cabin are before the turret, as are shown at *f f f*, &c., and the ward-room at F. The powder-magazines and ammunition are on each side of the berths, and a communication or passage is maintained throughout the whole length of the ship.

As a whole this is a clever well-designed vessel for a single turret and two heavy guns; she is exceedingly shallow for her length, but in order to stiffen her hull and keep her in shape, diagonal braces, *a a a a*, are attached to the interior of the turret, fig. 97, and at midships through the coal-bunkers *b b*, fig. 98. It will not be necessary to go further into detail, excepting only to direct attention to the decks, which are composed of a series of balks covered with an iron skin, for the purpose of preventing the entrance of shell into the interior below.

5. As regards armour-plated seagoing vessels, the Americans have not made much progress. During the war they were not requisite, as the Confederates had nothing to compete with them; and hence followed a description of monitors which can only be admired as floating batteries or well-shaped rafts, calculated for the destruction of forts and a similar description of craft in smooth water.

The following letters will also assist in facilitating reference to plates III. and IV., figs. 95 and 96.

*f f f*, &c.—Berths and cabin.
*g g*—Powder magazines.
*h h*—Stores for shells.
*k*—Solid shot stores.
*l*, &c.—Provision stores, pantries, &c.
*m*—The dispensary.
*n*—Bag room.
*o*—Water tanks.
*p p p*—Bureaus.
*s s*—Coal hatches.
*t t t*—Deck lights.

Digitized by Google

## CHAPTER XIII.

### ON THE COMPARATIVE MERITS OF SHIPS OF WAR.

1. Before closing the foregoing inquiry it may not be uninteresting briefly to recapitulate some of the leading facts contained in the different sections to which we have directed attention. It may be further useful to offer a few remarks on the investigations to which we have referred in the foregoing treatise, and consider how far they are applicable to the purposes for which they were written.

From what has been said, it is evident that iron—from its superior tenacity and susceptibility of being worked—is decidedly preferable to any other material with which we are acquainted for the construction of ships. It has its drawback as regards fouling; but having proved, by actual experiment, its superior powers of resistance to strain, we arrive at the conclusion that vessels intended either for war or for commerce should be built of iron or—what is probably the same thing, in these days of manufacturing progress—that ductile steel of uniform quality will entirely supersede the use of that material. When we consider the progress already made in chemical combination, and the future prospects held out for obtaining perfect homogeneity, greatly increased tenacity, and other corresponding improvements in the manufacture of this important article, we are of opinion that steel must eventually supplant the present manufacture of iron, establishing in its place a very superior quality of material, which applied to ships, boilers, bridges, and other similar constructions, will give nearly double the strength with the same weight of material.

Anticipating these results, we may venture to predict that timber will not often be used in the construction of a superior class of vessels, unless for special purposes, or in countries where it is cheap and abundant.

Digitized by Google

2. In the manufacture of armour-plates we have to contend with great difficulties before we can arrive at the thing desiderated—invulnerable ships. This, we fear, will never be accomplished so long as guns can be made of sufficient power to penetrate thicker plates than a vessel can carry; and there is probably no description of iron or steel armour-plates, either at present in use or in perspective, that are calculated to resist such powerful ordnance as the Armstrong 600-pounder gun.* It has already been noticed that the *complete* iron-clad ship is a ponderous inactive vessel, sluggish in her movements, a plunger at sea, and the growing conviction is, that just in proportion as the thickness of the plates is increased the ship is sunk deeper in the water, and rendered more unwieldy, more deficient in speed, and defective in those points essential to success in manœuvring round a superior force. Like the knights of old who—trusting to their armour—were no match for antagonists not weighed down with that incumbrance, depriving them of the power of action, and exposing them to the more agile and active manœuvres of an unincumbered enemy. As it was with men so it is with ships, and from the experience already attained, it becomes a question of vital importance to know to what extent the principle of iron-plating can be carried without endangering the sailing powers of the ship. Celerity of motion, great speed, and great facility in turning appear to be some of the most important elements of success in ships of war, and these, united to light vessels with powerful armaments, will constitute, according to our views, powers of aggression of the most formidable description.

3. What we have endeavoured to advocate in these pages is not to dispense entirely with armour-plates, but to apply them with careful attention to the more vulnerable parts of the ship so as not to injure her sailing powers, and other conditions necessary to the attainment of speed. We are of opinion that this may be done by a simple belt of plating (such as described p. 126) above and below the line of flotation. We have stated 5 feet above and 5 feet below that line, but a belt of 8 feet in

* Appendix II. *Vide* Sir William Armstrong's letter on the construction and power of guns.

Digitized by Google

depth would be—with a double bottom—a great protection, independently of any other consideration as regards the construction and the security of the ship. Most commanders can afford to lose a few men at the guns, but it becomes a question of much greater importance how to guard against the loss of the ship, and every plan that is calculated to give increased security to the vessel without impairing other important properties should be adopted. In a recent debate in the House of Commons on the Navy Estimates, Lord Clarence Paget made a very just statement of the merits and demerits of ships of war. He showed that complete protection by heavy armour-plates was incompatible with sailing qualities—that to adopt the one we must sacrifice the other; and hence it follows that we cannot thoroughly protect a ship against heavy guns without incurring an abortive construction totally unfit for service. If these views be correct there appears to be no better way of getting clear of the difficulty than the one we have ventured to recommend—namely, *a modified system of protection, by a narrow belt of thick armour-plating above and below the water-line, so as not to embarrass or retard the speed of the ship.*

Acting on these suggestions, it is gratifying to find that the Admiralty intend building four swift vessels with heavy armaments—not armour-plated, but trusting entirely to their speed, or, as Lord Clarence calls them, 'an improved class of Alabamas, calculated to outstrip every other description of vessel carrying the same number and weight of guns.'

Of this description of vessel the question arises, whether or not a partial amount of protection by armour-plates along the line of floatage would not be an improvement as regards the ship, and that without detriment to the steaming powers of the vessel. These are considerations which we must leave to more experienced heads than our own; and looking forward to this new condition of things, we may safely infer that they will receive from the authorities at Whitehall that attention to which they are so justly entitled.

4. In this work it is not our business to point out the proper size of ships, or the description of armaments best adapted for attack or defence; that is a question for the Admiralty and the experienced officers of Her Majesty's Navy to solve. We may,

Digitized by Google

nevertheless, venture to state that, in our opinion, a large class of vessels, such as the 'Minotaur,' 'Warrior,' and 'Achilles,' are not the best calculated for such a purpose. On the contrary, a smaller class, ranging from 2,000 to 3,000 tons burthen, appears to us much handier, and better adapted for heavy guns and high speed than the larger description of vessels of double the tonnage. They are, moreover, of sufficient magnitude to carry the necessary amount of armour-plating, and to preserve them from sinking under an enemy's fire.

5. We have not noticed what has been done by the French in carrying out this new system of protection, originally suggested and recommended by the Emperor, nor have we entered largely into what has been done by the Americans in that direction during the last four years of a destructive war. The French, like ourselves, have been experimenting on the resistance of plates and the strength of guns, and the whole or most of their ships have the armour-defences all round from 4 feet below the line of floatage to the upper deck. Most of their large ships are of wood covered with 4½-inch plates, excepting a little, above and below the water-line, where the plates are increased in thickness to 5 and in some cases to 6 inches. Some of the officers of the French Navy—in a conversation with the author—do not seem to attach much importance to the armour-plate system: they consider it experimental, and appear patiently to wait the result, and the changes consequent upon actual war, which they maintain is the only true criterion of its value.

L'Orient and Toulon are the principal ports for the construction of iron ships. At Rochefort and Brest they are all of wood, but ironclad from stem to stern, so as to attain the greatest efficiency in combat. This is, however, done at the expense of other qualities, and the complaint is that they pitch and labour at sea in foul weather to such an extent as to cause them to retrace their steps and to remove some of the iron-plating.

6. What the Americans—both Federals and Confederates—have done is chiefly gathered from the newspapers; but judging from the reports of Admiral Porter, given at page 153, we should infer that no advance has been made upon what has been done in this country and in France.

It would appear that the contrivances of the Great Republic

Digitized by Google

were produced to meet the necessities of the moment, and to provide for immediate service a class of vessels adapted to the navigation of the estuaries of their great rivers, and those points of attack occupied by the enemy in force. The constructions were therefore confined to flat-bottomed boats with turrets, and that class of monitors with single decks sunk almost level with the water, as described in Chapter XII.

7. The Government of this country and that of France have gone more systematically to work, and, guided by the aid of experiment, have constructed vessels of a much higher class; but, owing to the absence of that degree of experience which a maritime war is alone capable of furnishing, we arrive at the conclusion that the present construction, although far from perfect, is nevertheless in accordance with the present state of our knowledge; and although it may require to be modified, if not entirely changed, it is on the whole calculated to meet the exigencies of actual contest. To these changes and improvements we have no immediate guide, and, probably, we have no right to anticipate a state of things that belongs to futurity. For the present all that we can do is to act upon the results already obtained from target-practice; and, assuming that the effects of shot and shell in actual contest is not more destructive than what has been exhibited on targets, we may then conclude that the Iron Fleet of Great Britain is certainly not behind, if it is not considerably in advance, of any other maritime power in existence.

8. It has been demonstrated, and that demonstration has been confirmed by experiment, that the Iron Ship when properly designed and judiciously proportioned is considerably stronger and much more powerful in its resistance to strain than any other description of vessel. It applies rigidly to every class of vessel, whether intended for war or for commerce; and we have endeavoured to inculcate the principle, that all vessels intended for the navigation of the open sea should be made of iron. We are sensibly alive to the objections that may be urged against it, and amongst them as the most prominent is that of fouling, and the adhesion of shells and marine growths to the immersed surface of the ship. This is a serious drawback to the application of this useful material; but we have reason to believe that

Digitized by Google

some antidote for this evil—causing the retardation of speed—will, in the hands of our chemical friends, receive that attention which the importance of the subject demands, and that the time is fast approaching when immersed iron may become the repulsive instead of the attractive surface of adhesion. Impressed with these views, we have therefore not hesitated to recommend Iron as the only secure material for ship building. Iron, or Steel of the best quality, carefully distributed in its strongest forms, and applied with judgment in the construction of ships, *on the cellular system with double bottoms*, is in our opinion the only material that will meet the requirements of an effective navy, whether intended for war or commerce.

We have dwelt earnestly on this question as regards ships of war; and we cannot too forcibly express our opinion that much has yet to be done in both the war and the merchant service to secure efficient vessels, and effectually to provide for the comfort as well as the safety of a class of men to whom we are indebted for many of the enjoyments and blessings of life. It is for these men that we offer these remarks, and we entertain hopes that in the midst of all these changes the British seamen will, in the long run, have no reason to regret the transfer from the wooden walls of Old England to the safer and more enduring walls of the *Iron Ship*.

In conclusion, we would earnestly recommend the introduction of powerfully-built engines and boilers into all our vessels of war, so as to give them the speed requisite to escape from an enemy, or to attack him, as the emergency of the case may require. Vessels of war with powerful armaments and great speed possess immense advantages; *here the race is to the swift and the battle to the strong.* A single half knot per hour in excess of the speed of an enemy's ship may make all the difference between victory and defeat; and when we consider that it is more agreeable to deliver than to receive shot at high velocities on board ship, we arrive at the conclusion that we may safely leave the results, and all other matters of detail, in the hands of the officers and crews of Her Majesty's Navy.

Digitized by Google

# CHAPTER XIV.

## THE STRENGTH OF MATERIAL THEORETICALLY AND PRACTICALLY TREATED IN RELATION TO THE CONSTRUCTION OF IRON SHIPS.*

1. A FORCE acting on any rigid substance first tends to change the relative position of its fibres, and finally to separate them from each other. The property which all bodies possess, in a greater or less degree, of taking a new form under the action of a force, and of resuming their original form when the force is withdrawn, is called elasticity. In the following investigations it will be assumed that, under the action of equal forces, the extension of the fibres of a beam will be equal in amount to their compression, and that the amount of the extension or compression, as the case may be, is proportional to the magnitude of the force producing it; and in order to render this hypothesis more fully in accordance with the fact that the *ultimate* resistances of the two forces of compression and extension in a beam are in almost all cases different, it will be further assumed that the material reaches its ultimate limit of resistance to the one force before it reaches its ultimate limit of resistance to the other force.

### ELONGATION AND COMPRESSION.

2. *The modulus of elasticity* is that force, E, which is requisite to elongate a uniform bar, one square inch section, to double its length (supposing this possible), or to compress it to one half its length.

Let L = the length of a bar one square inch of section;

* It was originally intended to have given this chapter on the Strength of Materials (kindly furnished by Mr. Tate) at the beginning of the work; but owing to certain arrangements, in connection with the explanatory drawings and other matters, this could not be accomplished; we have consequently been necessitated to give it at the close in place of giving it at the commencement of the volume.

Digitized by Google

$l$ = its elongation or compression with a force $p$; then from the assumed law of elasticity, we get—

$$p = \frac{\text{E}\, l}{\text{L}} \quad \ldots (1)$$

If the bar contains K square inches in the section, then—

$$\text{P} = \text{K times } p = \frac{\text{E K}\, l}{\text{L}} \quad \ldots (2)$$

Or if the value of $l$ be required, we have—

$$l = \frac{\text{P L}}{\text{E K}} \quad \ldots (3)$$

In these expressions, L and $l$ are in the same linear unit, as well as P and E.

*To find the* WORK *expended in the elongation of a bar,* whose section is K square inches, and its length L feet.

3. Let $l$ represent the elongation produced by the strain of P lbs., then by eq. (2), $\text{P} = \frac{\text{E K}}{\text{L}} l$, and the *work* expended in this elongation will be—

$$\text{U} = \int_0^l \text{P}\, d\, l = \frac{\text{E K}}{\text{L}} \int_0^l l\, d\, l = \tfrac{1}{2} \frac{\text{E K}}{\text{L}} l^2 \quad \ldots (4)$$

where *the work varies as the square of the elongation.*

Substituting P for its value, above given, we get—

$$\text{U} = \tfrac{1}{2} \text{P}\, l \quad \ldots (5)$$

where *the work is equal to one-half the strain multiplied by its corresponding elongation.*

Eliminating $l$, we get—

$$\text{U} = \tfrac{1}{2} \frac{\text{L}}{\text{E K}} \text{P}^2 \quad \ldots (6)$$

where the *work varies as the square of the greatest strain.*

4. If P be the ultimate strain, then $\text{P} = \text{K S}$, and eq. (6) becomes—

$$\text{U} = \tfrac{1}{2} \frac{\text{S}^2}{\text{E}} \text{K L} \quad \ldots (7)$$

where the *work varies as the sectional area multiplied by the length,* or *as the solid content of the bar.*

Now let $u$ be put for the work done when L and K are equal to unity; then $u = \frac{1}{2} \frac{\text{S}^2}{\text{E}}$, which is *a constant for the same material*; therefore eq. (7) becomes—

$$\text{U} = u \text{ K L} \quad \ldots (8)$$

Digitized by Google

where $u$ is the work done upon a bar one foot long and one square inch in section.

The value of $u$, determined for different kinds of material, gives us a comparative measure of their powers of resistance to a strain of the nature of impact, or of dynamic effect; hence the coefficient, U, may be called *the modulus of dynamic resistance.*

5. To determine $u$ from experimental data for different kinds of material.

From eq. 8, and substituting the different values of U, we get—

$$u = \frac{U}{K L} = \tfrac{1}{2} \frac{E l^2}{L^2} \text{ or } \tfrac{1}{2} \frac{P^2}{E K^2} \text{ or } \tfrac{1}{2} \frac{P l}{K L} \quad \ldots (9)$$

For bars of the same length and section, but different material—

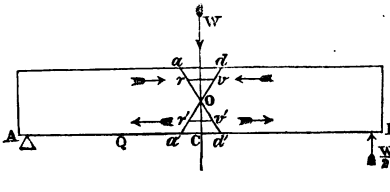
$$\frac{u}{u_1} = \frac{P l}{P_1 l_1} \quad \ldots (10)$$

THE NEUTRAL AXIS OF A BEAM.

6. Let us suppose that a beam, A B, rests upon two props, as shown in fig. 99, and that it has a weight, W, placed upon its middle, then this weight causes the beam to bend, and thereby gives rise to a complex action in the fibres of the material: the fibres at the top part of the beam become compressed, while those at the bottom part become extended, and there is a certain line of fibres in the beam which are neither compressed nor extended; this portion is called the plane of the neutral axis. The position of this axis depends upon the form of the transverse section of the beam. If this section be rectangular, the neutral axis will obviously lie in a line passing through the centre of the section; in general the neutral axis will lie towards the part where the material presents the greatest resistance, so that *the sum of the forces of resistance on each side of the axis may be duly balanced, or equal to each other.*

7. If o be the neutral axis of the section of rupture, then the fibres, $r v$, &c., on the upper side of o, will undergo compression, while the fibres, $r' v'$, &c., on the lower side will undergo extension. The elongations, $r' v'$, &c., and the compressions,

Fig. 99.




Digitized by Google

$r\ v$, &c., are proportional to their distances, o $v'$, o $v$, from the neutral axis, o. But as the strains in the direction of the fibres are in the ratio of the corresponding elongations and compressions, they are therefore also in the ratio of their distances from the neutral axis; thus, if $s$ be put for the resistance of a unit of surface at a unit of distance from o, then the compressive resistance of the small surface $k_1$, at the distance $z_1$ from the neutral axis will be expressed by $s\ z_1\ k_1$, and so on to the resistance of $k_2$, $k_3$, &c., at the distances $z_2$, $z_3$, &c., respectively; hence

The sum of these resistances to compression

$$= s\ z_1\ k_1 + s\ z_2\ k_2 + \&c. = s\ (z_1\ k_1 + z_2\ k_2 + \&c.)$$

Similarly, the sum of the tensile resistances

$$= s\ (z'_1\ k'_1 + z'_2\ k'_2 + \&c.)$$

$$\therefore z_1\ k_1 + z_2\ k_2 + \&c. = z'_1\ k'_1 + z'_2\ k'_2 + \&c.$$

This equality shows that the neutral axis lies in the centre of gravity of the section. Thus, if $a$ and $a_1$ be put for the areas of the section of the material above and below the neutral axis respectively, $g$ and $g_1$ the respective distances of their centres of gravity, then

$$a\ g = a_1\ g_1 \ \ldots \ (1)$$

Or if $\alpha$ and $\alpha_1$ be elements of surface, then

$$\Sigma\ \alpha\ g = \Sigma\ \alpha_1\ g_1 \ \ldots \ (2)$$

8. The neutral axis of any beam will be most readily found by referring the moments of the surfaces of the section to some convenient axis of moments. For example, let it be required to find the neutral axis, N O, of a tubular girder, whose section is represented by fig. 121; where the area of the material in the top section, A B F E $= a_0$; area bottom C D $= a_1$; area two side plates $= a_2$; the distances of the centres of gravity of these areas respectively from the upper edge A B of the section $= \alpha_0, \alpha_1, \alpha_2$; K = the area of the whole section; $h$ = A N = B O, the distance of the neutral axis from A B; then taking the line A B as the axis of moments, from the common property of the centre of gravity, we get

$$h = \frac{1}{K}\ (a_0\ \alpha_0 + a_1\ \alpha_1 + a_2\ \alpha_2) \ \ldots \ (3)$$

If $d$ be the depth of the girder, and $h_1$ the distance of the lower edge C D from the neutral axis, then

$$h_1 = d - h \ \ldots \ (4)$$

Digitized by Google

When the top section is symmetrical with the bottom section, the neutral axis obviously lies in the centre of the section.

### CONDITIONS OF TRANSVERSE RUPTURE.

9. In the beam described, Art. 6, fig. 99, the weight W will produce a pressure of $\frac{W}{2}$ upon each of the supports A and B; now as the beam turns round on O as a fulcrum, this pressure acting at B will have a leverage of half the distance between the supports, or $\frac{1}{2}$ A B; hence the moment of the weight W tending to rupture the beam at the middle C will be equal to $\frac{W}{2} \times \frac{A B}{2}$ or $\frac{W \times A B}{4}$, which we shall represent by the symbol M. This is called the moment of rupture, it being always equal to the sum of the moments of the resistances of the material in the section about to undergo rupture.

Adopting the notation of Art. 7, the compressive forces of resistance of the several elements of surface, $k_1$, $k_2$, &c., are $s z_1 k_1$, $s z_2 k_2$, &c.; but these forces respectively act with the leverages, $z_1$, $z_2$, &c., so that the sum of the moments of all these forces of compression

$$= s z_1^2 k_1 + s z_2^2 k_2 + \&c. = s (z_1^2 k_1 + z_2^2 k_2 + \&c.)$$

In like manner, the sum of the moments of all the forces of extension $= s (z'_1{}^2 k'_1 + z'_2{}^2 k'_2{}^2 + \&c.)$.

But it appears from works on mechanics that the quantities within the brackets express *the moments of inertia* of the respective sections, therefore putting I for the moment of inertia of the section above the neutral axis, $I_1$ for that below this axis, and $I_0$ for the moment of inertia of the whole section about its centre of gravity or the neutral axis of the whole section; then $s$ I will be the sum of the moments of resistance to compression of the material above the neutral axis, and $s$ $I_1$ will be the moments of resistance of the material below the neutral axis; but the sum of these moments is equal to the moment, M, of the resistance of the whole section; hence we have

$$M = s I + s I_1 = s I_0 \ldots (1)$$

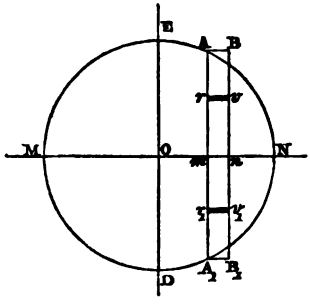
10. The values of I and $I_1$ depend solely on the geometrical form of the transverse section of the beam.



Digitized by Google

Let M O N represent the neutral axis of the rectangular sections A B $m n$ and $A_1 B_1 m n$; put $h = A m$, $h_1 = A_1 m$, $b = AB$, $b_1 = A_1 B_1$, $x = n v$, $b \Delta x$ = area element of surface $r v$; then the compressive resistance of the element $r v = b \Delta x \times s x = s b x \Delta x$, and therefore the moment of this element $= s b x \Delta x \times x = s b x^2 \Delta x$;

Fig. 100.




$\therefore$ The sum of all the moments between $r v$ and A B, or the moment of resistance of the rectangle A B $r v$

$$= s\ b\ \Sigma_x^h\ x^2\ \Delta\ x = s\ b \int_x^h x^2\, dx$$

$$= \tfrac{1}{3} s b (h^3 - x^3) = s\, I \ldots (2)$$

$$\therefore I = \tfrac{1}{3} b (h^3 - x^3) \ldots (3)$$

which is the moment of inertia of the rectangle A B $r v$ about the base $m n$.

Similarly, $$I_1 = \tfrac{1}{3} b_1 (h_1^3 - x^3) \ldots (4)$$

And when $x = 0$, $$I = \tfrac{1}{3} b h^3 \ldots (5)$$

which is the moment of inertia of the rectangle A B $n m$ about its base $m n$.

Now if we regard A B $m n$ as the element of the section M E A N, bounded by any line, the moment of inertia, I, of this section will be $\tfrac{1}{3} \Sigma b h^3$; putting, therefore, $y$ for $h = A m$, $x = O m$, and $\Delta x$ for $b = m n$, this expression becomes,

$$I = \tfrac{1}{3} \Sigma y^3 \Delta x = \tfrac{1}{3} \int y^3 dx \ldots (6)$$

where the limits of integration remain to be assigned. If the limits be taken between $x = 0$ and $x$, then the moment of inertia of the space O E A $m$ will be

$$I = \tfrac{1}{3} \int_0^x y^3 dx \ldots (7)$$

11. Let $h = A N = B O$, the distance of the upper edge A B of the section of rupture from the neutral axis N O (see fig. 121); $h_1 = N C = O D$, the distance of the lower edge from the neutral axis; $s$ = the resistance of the material, per square inch, to compression at the upper edge; $s_1$ = the resistance of the material, per square inch, to extension at the lower edge; then

$$s = \frac{s}{h} = \frac{s_1}{h_1} = \ldots (8)$$

Digitized by Google

$$\therefore M = s(I + I_1) = s I_0$$
$$= \frac{S}{h} I_0 \text{ or } \frac{S_1}{h_1} I_0 \ldots (9)$$

12. *When the depth and the amount of material in the transverse section are given; to determine the distribution of the material so that the beam may have the greatest strength.*

The first and most important condition of maximum strength is, that the material should be accumulated, as far as practicable, at the upper and lower edges of the beam.

The next condition of maximum strength determines the relative amount of the material on each side of the neutral axis. The principle upon which this distribution of material depends is this: when the material at the upper edge of the beam is upon the point of yielding by compression, the material at the lower edge must at the same time be upon the point of yielding by extension; hence

$$\frac{S}{h} = \frac{S_1}{h_1}, \text{ or } \frac{S}{S_1} = \frac{h}{h_1} \ldots (1)$$

that is, the *distances of the neutral axis from the upper and lower edges of the beam should be in the ratio of the ultimate resistances of the material at these parts respectively.*

If $r = \frac{S}{S_1}$, and D = the whole depth of the beam; then

$$h = \frac{r D}{r + 1} \ldots (2), \text{ and } h_1 = \frac{D}{r + 1} \ldots (3)$$

In the case of wrought iron, $r = \frac{5}{6}$ nearly, that is, the ultimate resistance of wrought iron to compression is about $\frac{5}{6}$ of its ultimate resistance to extension.

In tubular girders where the material is accumulated at the upper and lower edges of the girder, the sectional areas at these parts should, obviously, be in the inverse ratio of the ultimate resistances of the material at these parts respectively.

### TO CHANGE THE AXIS OF MOMENTS.

13. Let N O (fig. 121) be the neutral axis of the section passing through the centre of gravity, and G K any other axis parallel to N O at the distance $\bar{x}$ from it; $I + I_1 = I_0$ = the moment of inertia of the whole section referred to the axis N O; $I' + I'_1 = I_x$ = the moment of inertia of the section referred to the axis



Digitized by Google

G K; the other notation being the same as in the preceding investigations.

By eq. (3) Art. 10, putting $e$ for $x$ we get

$$\text{I} = \Sigma \frac{b}{3}(h^3 - e^3)$$

$$\therefore \text{I}' = \Sigma \frac{b}{3}\{(h + \bar{x})^3 - (e + x)^3\}$$

by reduction, observing that $a = b\,(h-e)$, and $g = \frac{1}{2}(h + e)$,

$$\text{I}' = \text{I} + 2\bar{x}\,\Sigma\, a\, g + \bar{x}^2\,\Sigma\, a$$

Similarly, substituting $-\bar{x}$ for $\bar{x}$, &c., we get

$$\text{I}'_1 = \text{I}_1 - 2\bar{x}\,\Sigma\, a_1\, g_1 + \bar{x}^2\,\Sigma\, a_1$$

$$\therefore \text{I}_x = \text{I}' + \text{I}'_1 = \text{I} + \text{I}_1 + 2\bar{x}\,(\Sigma\, a\, g - \Sigma\, a_1 g_1) + \bar{x}^2\,(\Sigma\, a + \Sigma\, a_1)$$

$$= \text{I}_0 + \bar{x}^2\,\text{K} \quad \ldots \quad (1)$$

$$\therefore \text{I}_0 = \text{I}_x - \bar{x}^2\,\text{K} \quad \ldots \quad (2)$$

Hence it appears, that *the moment of inertia of the section about its neutral axis*, or the line passing through its centre of gravity, *is equal to the moment of inertia taken with respect to any other parallel axis, minus the square of the distance between these axes multiplied by the area of the whole section.*

This formula will be found useful in calculating the moments of inertia of complex sections.

### TRANSVERSE STRAINS PRODUCED ON BEAMS UNDER VARIOUS CONDITIONS.

14. The value of M, or the strain tending to rupture a beam, depends on the magnitude and the relative position of the pressures applied to the beam.

When the pressure, W, is applied at the middle of the beam, A B, supported at its extremities, fig. 99, the pressure on the support at A is equal to $\frac{W}{2}$; and the moment, $M_1$, of this pressure, tending to rupture the beam at *any* point Q is equal to the product of the pressure $\frac{W}{2}$ by its leverage A Q, that is,

$$M_1 = \frac{W}{2} \times \text{A Q} \quad \ldots \quad (1)$$

Now this will become a maximum when A Q = A C; that is, the greatest strain will take place at the centre of the beam, or at the point where the weight is applied.

Digitized by Google

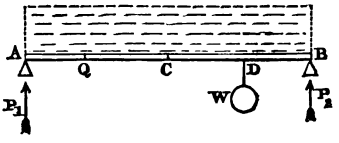
15. When a beam is supported at the extremities, and the pressure W is applied at any point D (fig. 101): to find M.

Putting $P_1$ and $P_2$ for the pressures on the props, A and B, we find

$P_1 \times AB = W \times DB$; $\therefore P_1 = W \times \frac{DB}{AB}$;

and similarly, $P_2 = W \times \frac{DA}{AB}$.

Fig. 101.




Now, to produce rupture at D, the pressure $P_1$ will act with the leverage AD;

$$\therefore M = P_1 \times AD = W \times \frac{AD \times DB}{AB} \quad \ldots \quad (2)$$

The same result is obtained by taking the moment $P_2 \times DB$.

Now this will be a maximum when the product of AD and DB is a maximum, but we know that this takes place when AD is equal to DB; that is to say, the given weight will produce the greatest strain on the beam when it is applied at the centre, C; in this case, eq. (2) becomes

$$M = W \times \frac{AC \times AC}{AB} = \frac{W \times AB}{4} \text{ or } \frac{W \times AC}{2} \quad \ldots \quad (3)$$

The moment of $P_1$, tending to rupture the beam at any point Q, varies as the distance of this point from A, that is,

$$M_1 = P_1 \times AQ = W \times \frac{DB \times AQ}{AB} \quad \ldots \quad (4)$$

And when W is applied at the centre, C, this becomes

$$M_1 = \frac{W}{2} \times AQ \quad \ldots \quad (5)$$

16. When the load, W, is distributed *uniformly throughout the length of the beam.* To find $M_1$, the moment tending to rupture the beam at any point Q. See fig. 101.

Here the pressure, $P_1$, on the prop A will be $\frac{W}{2}$, or one half the whole load on the beam, and the weight over the part AQ will be $\frac{W \times AQ}{AB}$, acting with the leverage $\frac{AQ}{2}$,

$$\therefore M_1 = P_1 \times AQ - \frac{W \times AQ}{AB} \times \frac{AQ}{2} = \frac{W}{2} \times AQ - \frac{W}{2} \times AQ \times \frac{AQ}{AB}$$

$$= \frac{W \times AQ \times QB}{2\,AB} \quad \ldots \quad (6)$$

Now this will become a maximum when $AQ = QB$; that is,

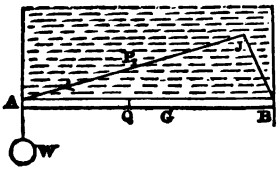
Digitized by Google

when the point is at the middle, C, of the beam. In this case, eq. (6) becomes

$$M = \tfrac{1}{8} W \times AB \quad \ldots \quad (7)$$

17. When the beam, AB, is *fixed at the extremity* B, and loaded with the weight, W, at the other extremity. In this case, the moment, $M_1$, tending to rupture the beam at any point, Q, will be

Fig. 102.




$$M_1 = W \times AQ \quad \ldots \quad (8)$$

This will, obviously, be greatest at B, and then

$$M = W \times AB \quad \ldots \quad (9)$$

1. If the pressure, $P_1$, be *applied obliquely*, BJ being a perpendicular let fall upon the line in which the pressure acts, then BJ will be the effective leverage of the pressure, and

∴ The moment tending to rupture the beam at B

$$= P_1 \times BJ = P \times AB \times \sin \angle BAJ \quad \ldots \quad (10)$$

18. When the load, W, is distributed *uniformly throughout the length of the beam.* To find $M_1$, the moment tending to rupture the beam at any point Q. See fig. 102.

Here the weight over AQ is $\frac{W \times AQ}{AB}$, which acting in its centre of gravity, or at the distance $\frac{AQ}{2}$ from the point Q, gives

$$M_1 = \frac{W \times AQ^2}{2\,AB} \quad \ldots \quad (11)$$

This becomes a maximum when AQ = AB, or when the point of rupture is at B. In this case, eq. (11) becomes

$$M = \frac{W \times AB}{2} \quad \ldots \quad (12)$$

19. A beam, AB, *fixed at the extremity* B (fig. 102), is acted upon by *a series of vertical pressures*, $p_1$, $p_2$, . . . $p_n$, whose distances from B are respectively $a_1$, $a_2$, . . . $a_n$. To find the maximum value of M.

Here the greatest strain must take place at B;

$$\therefore M = p_1 a_1 + \ldots + p_n a_n = (p_1 + \ldots + p_n)\, GB \quad \ldots \quad (13)$$

Where GB is the distance of the centre of gravity of all the pressures from the point of support B.

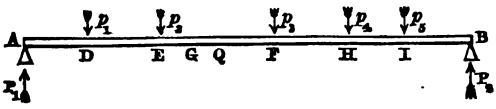
20. A beam, AB, *supported at its extremities*, is acted upon

Digitized by Google

by *a series of pressures* on each side of the central pressures, $p_2$, $p_3$, $p_4$, applied at the points E, F, H. To find the greatest value of M. See fig. 103.

Let $p_1$ be the resultant of the pressures applied between A

Fig. 103.




and E, and $p_5$ the resultant of those applied between B and H. By the principle of the equality of moments, we get

$$P_1 = \frac{1}{AB}(p_1 \times DB + p_2 \times EB + p_3 \times FB + p_4 \times HB + p_5 \times IB)$$

$$= \frac{1}{AB}(p_1 + \ldots + p_5) GB = \frac{W \times GB}{AB} \quad \ldots (14)$$

which gives the pressure on the prop A, where W is put for the sum of the pressures, and G is their centre of gravity.

Supposing Q, lying between the pressures $p_2$ and $p_3$, to be the point corresponding to the greatest strain, or in fact, the point where rupture would take place in a beam of uniform dimensions.

Now when the lever AQ turns on Q as a centre, we get

$$M = P_1 \times AQ - (p_1 \times DQ + p_2 \times EQ)$$

$$= (P_1 - p_1 - p_2) AQ + p_1 \times AD + p_2 \times AE$$

$$= \frac{AQ}{AB}\{W \times GB - AB(p_1 + p_2)\} + p_1 \times AD + p_2 \times AE \quad \ldots (15)$$

by substituting the value of $P_1$ given in eq. (14).

Substituting the value of $W \times GB$ given in eq. (14), and putting $g_1$ for the distance of the centre of gravity of $p_1$, $p_2$ from A, and $g_2$ for that of $p_3$, $p_4$, $p_5$ from B, we get

$$M = \frac{AQ}{AB}\{(p_3 + p_4 + p_5) g_2 - (p_1 + p_2) g_1\} + (p_1 + p_2) g_1 \quad \ldots (16)$$

By *interchanging* the symbols of this expression, the moment taken in reference to the pressure $P_2$ will be

$$M = \frac{BQ}{AB}\{(p_1 + p_2) g_1 - (p_3 + p_4 + p_5) g_2\} + (p_3 + p_4 + p_5) g_2$$

This expression may be shown to be identical with the former by putting AB − AQ for BQ.

Digitized by Google

Similarly, supposing the point Q to lie between F and H, we get

$$M = \frac{AQ}{AB}\{W \times GB - AB(p_1+p_2+p_3)\}$$

$$+p_1 \times AD + p_2 \times AE + p_3 \times AF \ldots (17)$$

Now if the quantity within the brackets of eq. (15)is positive, while that of eq. (17) is negative, the value of M, expressed by eq. (15), will increase with AQ attaining a maximum at F, on the other hand, the value of M, expressed by eq. (17), will increase as AQ is decreased, attaining a maximum at F; hence it follows that the point F, under these conditions, will undergo the greatest strain, and eq. (15) will express the maximum value of M by substituting AF for AQ. The test for the point, F, of greatest strain being as follows:—

$$W \times GB - AB(p_1 + p_2) = \text{positive} \ldots (P)$$

$$W \times GB - AB(p_1 + p_2 + p_3) = \text{negative} \ldots (N)$$

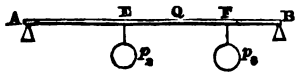
*Example.*—Let AB = 40, $p_1 = 6$, $p_2 = 10$, $p_3 = 20$, $p_4 = 8$, $p_5 = 6$ tons, DB = 32, EB = 25, FB = 22, HB = 12, IB = 4. Then from (P) and (N), we find that F is the point of greatest strain, and from eq. (15), we find M, the greatest moment tending to rupture the beam, to be 361 nearly.

21. When $W \times GB = AB(p_1 + p_2)$, or $(p_3 + p_4 + p_5)g_2 = (p_1 + p_2)g_1$, eq. (15) becomes,

$$M = p_1 \times AD + p_2 \times AE \ldots (18)$$

Now as this expression is independent of AQ, it follows that *the value of* M *is the same for all points lying between* E *and* F. This remarkable result may be readily verified by observing that, in this case, $P_1 = p_1 + p_2$.

Fig. 104.




22. When there are only two pressures, $p_2$, $p_3$, applied to the beam, that is, when $p_1 = p_4 = p_5 = 0$ (see fig. 104), then eq. (16) becomes

$$M = \frac{AQ}{AB}(p_3 \times BF - p_2 \times AE) + p_2 \times AE \ldots (19)$$

If $p_3 \times BF > p_2 \times AE$, then M becomes a maximum at F, that is, AQ = AF.

When $p_3 \times BF = p_2 \times AE$, then this expression becomes

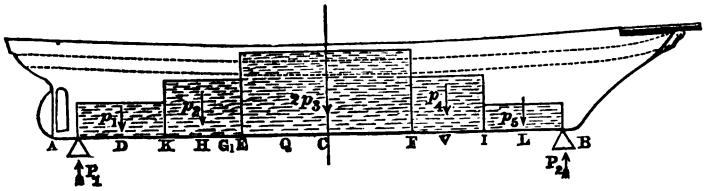
$$M = p_2 \times AE \text{ or } p_3 \times BF \ldots (20)$$

which being independent of AQ, shows that *the moment is constant for all points lying between* E *and* F.

Digitized by Google

23. *When a ship has its load unequally distributed throughout its length.* To find the point of maximum strain, &c., the ship being supported at the extremities A and B.

Fig. 105.




Suppose the ship to be uniformly loaded over the parts A K, K E, &c., and let $p_1, p_2$, &c., be the loads over these parts respectively. Put $l$ = A B; $k_1$ = A E; $k$ = E F; $k_2$ = F B; $a$ = C B, the centre of gravity of E F being at C; $w_1$ = the weight of the mass over A E, $g_1$ = the distance of its centre of gravity from A; $w_2$ = the weight of the mass over F B, $g_2$ = the distance of its centre of gravity from B; $2p_3$ = the weight of the mass over E F; $x$ = A Q, the greatest strain being supposed at Q; then

$$P_1 = \frac{1}{l}\{w_1(l - g_1) + 2p_3 a + w_2 g_2\} \quad \ldots \quad (1)$$

$$M = P_1 \times AQ - w_1(AQ - g_1) - \frac{2p_3}{k} \times (AQ - AE) \times \tfrac{1}{2}(AQ - AE)$$

$$= P_1 x - w_1(x - g_1) - \frac{p_3}{k}(x - k_1)^2 \ldots (2);$$

$$\therefore \frac{dM}{dx} = P_1 - w_1 - \frac{2p_3}{k}(x - k_1) = 0, \text{ when } M \text{ is a max.}$$

$$\therefore x = \frac{1}{2p_3}\{k(P_1 - w_1) + 2k_1 p_3\} \ldots (3)$$

Substituting the value of $P_1$, given in eq. (1), this expression determines the point, Q, of greatest strain; and substituting the values of $P_1$ and $x$, here found, in eq. (2), the maximum value of M will be determined.

1. If $w_1 g_1 = w_2 g_2$, and $k_1 = k = k_2 = \frac{l}{3}$, then from eq. (1), we get, $P_1 = w_1 + p_3$, which substituted in eq. (3) gives $x = \frac{l}{2}$, that is, the point of greatest strain is at the centre.

Again, substituting these values in eq. (2), we get

$$M = \frac{5}{12} p_3 l + w_1 g_1 \quad \ldots \quad (4)$$

Digitized by Google

2. If $2\,p_3 = 0$, and $w_1\,g_1 = w_2\,g_2$; then $P_1 = w_1$, and $M = w_1\,g_1$, which expresses the moment tending to rupture all points lying between E and F.

24. Suppose the length of the ship to be divided into six equal spaces, A K, K E, E C, C F, F I, I B, the loads on each part being $p_1$, $p_2$, $p_3$, $p_3$, $p_4$, &c. respectively; then

$$AK = KE = \&c. = \frac{l}{6}, \text{ and}$$

$$P_1 = \frac{1}{l}\{p_5 \times LB + p_4 \times VB + \&c.\}$$

$$= \frac{1}{12}\{p_5 + 3\,p_4 + 5\,p_3 + 7\,p_2 + 9\,p_2 + 11\,p_1\} \ldots (5)$$

$$M = P_1 x - p_1\left(x - \frac{l}{12}\right) - p_2\left(x - \frac{l}{4}\right) - \frac{3\,p_3}{l}\left(x - \frac{l}{3}\right)^2 \ldots (6)$$

And to render M a maximum, we find

$$x = \frac{l}{2}\left\{1 - \frac{3\,(p_2 - p_4) + p_1 - p_5}{36\,p_3}\right\} \ldots (7)$$

The values of $P_1$ and $x$, substituted in eq. (6), give the greatest moment, M, tending to rupture the ship.

1. If $p_5 = p_1$, and $p_4 = p_2$, then eq. (7) becomes $x = \frac{l}{2}$, that is, the greatest strain will be at the centre C.

And from eq. (5), we find, $P_1 = p_1 + p_2 + p_3$;
and substituting in eq. (6), we get

$$M = \frac{l}{12}(p_1 + 3\,p_2 + 5\,p_3) \ldots (8)$$

If $\frac{W}{2}$ be put for the sum of the pressures, $p_1$, $p_2$, $p_3$, on each half of the ship, and let $G_1$ be the centre of gravity of these pressures, then

$$M = P_1 \times AC - \frac{W}{2} \times G_1C = \frac{W}{2} \times AC - \frac{W}{2} \times G_1C$$

$$= \frac{W}{2} \times AG_1 \ldots (9)$$

that is, the moment tending to rupture the beam at the centre is equal to the load on one-half of the ship multiplied by the distance of its centre of gravity from the extremity.

25. Now let us suppose that the ship is balanced upon its centre C (see fig. 105); then, in this case, the greatest strain will obviously be at the point of support C; hence we have

Digitized by Google

$$\text{M} = p_1 \times \text{D C} + p_2 \times \text{H C} + p_3 \times \tfrac{1}{2}\,\text{E C};$$

but $\text{D C} = \frac{5}{12}\,l$, $\text{H C} = \frac{3}{12}\,l$, and $\frac{1}{2}\,\text{E C} = \frac{1}{12}\,l$,

$$\therefore \text{M} = \frac{l}{12}\,(5\,p_1 + 3\,p_2 + p_3) \ldots (10)$$

Or proceeding as in eq. (9), we get

$$\text{M} = \frac{\text{W}}{2} \times \text{G}_1\,\text{C}, \text{ or } \frac{\text{W}}{2}\left(\frac{l}{2} - \text{A G}_1\right) \ldots (11)$$

Comparing this expression with eq. (9), it will be observed, that as the load is accumulated towards the centre of the ship, $\text{A G}_1$ will be greater than $\text{G}_1\,\text{C}$, and therefore (9) will be greater than (11).

26. If the load be equally distributed, or $p_1 = p_2 = \&c. = \frac{\text{W}}{6}$, then $\text{A G}_1 = \frac{1}{2}$ of $\frac{l}{2} = \frac{l}{4}$, and eq. (9) becomes

$$\text{M} = \frac{\text{W}}{2} \times \frac{l}{4} = \frac{\text{W}\,l}{8} \ldots (12)$$

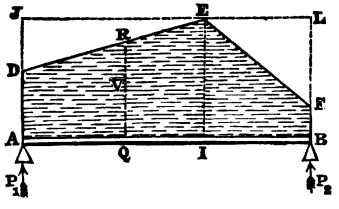
and from eq. (11) we get

$$\text{M} = \frac{\text{W}}{2}\left(\frac{l}{2} - \frac{l}{4}\right) = \frac{\text{W}\,l}{8} \ldots (13)$$

Where the results of eq. (12) and (13) are the same; that is to say, the moments tending to rupture the ship, in the two positions, are the same, when the load is uniformly distributed throughout its length.

27. When the load has the form of a trapezoidal figure A D E L P. To find the greatest moment tending to rupture the beam A B, supported at its extremities.

Fig. 106.




Let $\text{A B} = l$, $\text{A I} = a$, $\text{I B} = a_1$, $\text{E I} = e$, $\text{A D} = b$, $\text{B F} = b_1$, $\text{A Q} = x$, $\mu$ = the weight of a unit of surface in the load.

Now, observing that the moment of the surface A D E F B is equal to the moment of the rectangle A J L B, minus the sum of the moments of the triangles D J E and E L F, we find after reduction

$$\text{P}_1 = \frac{\mu}{6\,l}\ \{\, 3\,e\,l^2 - a\,(e-b)\,(2\,a + 3\,a_1) - (e-b_1)\,a_1^2 \,\} \ldots (1)$$

When $a_1 = a$, this expression becomes,

Digitized by Google

$$P_1 = \frac{\mu a}{12}(6e + 5b + b_1) \ldots (2)$$

The trapezoid A D R Q being composed of the rectangle A D V Q and the triangle D V R, we have

$$M = P_1 x - \mu b x \times \frac{x}{2} - \frac{x}{2} \times \frac{e-b}{a} \times x \times \mu \times \tfrac{1}{3} x$$

$$= P_1 x - \tfrac{1}{2}\mu b x^2 - \tfrac{1}{6}\mu \frac{e-b}{a} x^3 \ldots (3)$$

Hence we have for the maximum value of M,

$$\frac{dM}{dx} = P_1 - \mu b x - \frac{\mu(e-b)}{2a} x^2 = 0$$

$$\therefore x = \frac{a}{e-b}\left\{\sqrt{\frac{2(e-b)}{\mu a} P_1 + b^2} - b\right\} \ldots (4)$$

Which gives the point, Q, where the greatest strain takes place. The values of $P_1$ and $x$ being substituted in eq. (3), we find the maximum value of M as required.

1. When $a_1 = a$, then $P_1$ is expressed by eq. (2), and we get

$$x = \frac{a}{e-b}\{\sqrt{\tfrac{1}{6}(e-b)(6e + 5b + b_1) + b^2} - b\} \ldots (5)$$

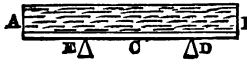
Substituting these values in eq. (3), we find the maximum moment required.

2. When $b_1 = b$, in the last equalities, we find $x = a$, that is, the greatest strain will take place in the centre of the beam, and from eq. (3) and (2) we get

$$M = \tfrac{1}{6}\mu a^2(2e + b) \ldots (6)$$

28. A beam, A B, uniformly loaded throughout its length, is supported by two props, E and D, placed at equal distances from its extremities. To determine the conditions of rupture.

Fig. 107.




Here the greatest strains obviously take place at the centre C, and at the points of support E and D.

Let M, $M_1$ be put for the moments tending to rupture the beam at C and E respectively; $a = A C = C B$; $a_1 = D B = E A$; $\mu =$ the load upon each unit of length of the beam.

Now, the pressures on the supports being equal to each other, the pressure on E will be $a\mu$,

$$\therefore M = \text{pressure at E} \times E C - W t . A C \times \tfrac{1}{2} A C$$

$$= a\mu(a - a_1) - a\mu \times \tfrac{1}{2} a = a\mu(\tfrac{1}{2}a - a_1) \ldots (1)$$

Similarly, we get

Digitized by Google

$$M_1 = W t \cdot AE \times \tfrac{1}{2} AE$$
$$= a_1 \mu \times \tfrac{1}{2} a_1 = \tfrac{1}{2} a_1^2 \mu \ \ldots \ (2)$$

*The best position of the props* will be attained when $M_1 = M$; hence we have, by equating (1) and (2),

$$a \mu (\tfrac{1}{2} a - a_1) = \tfrac{1}{2} a_1^2 \mu$$

Solving this equation for the value of $a_1$, we find

$$a_1 = a (\sqrt{2} - 1) = \cdot 414\, a \ \ldots \ (3)$$

which gives the length of AE or BD when the props have the best position.

29. The following is a summary of the most useful results of the foregoing investigations.

Putting $l$ = the length of beam; $W$ = the whole load on the beam; $M$ = the greatest moment tending to rupture the beam.

*Case* 1. When the beam is loosely supported at its extremities and loaded in the middle.

$$M = \frac{W l}{4}$$

*Case* 2. When a projecting beam is firmly supported at one extremity and loaded at the other extremity.

$$M = W l$$

*Case* 3. When the beam is loosely supported at its two extremities, and the load uniformly distributed throughout the length of the beam.

$$M = \frac{W l}{8}$$

Here the value of $M$ is one-half of that given in Case 1.

*Note.* When the beam is firmly fixed at its extremities.

$$M = \frac{W l}{24}$$

*Case* 4. When a projecting beam is firmly supported at one extremity, and the load uniformly distributed over the beam.

$$M = \frac{W l}{4}$$

Here the value of $M$ is double that of Case 3, and one-fourth that of Case 2.

*Case* 5. When the beam is supported at its extremities and unequally loaded, but the load being symmetrically distributed on each side of the centre.

Digitized by Google

$$M = \frac{W \times G_1}{2}$$

Where $G_1$ is put for the distance of the centre of gravity of each half of the load from the corresponding extremity.

*Case* 6. When a projecting beam is firmly supported at one extremity and unequally loaded.

$$M = W \times G_1, \text{ or } W(l - G_1)$$

Where $G_1$ is put for the distance of the centre of gravity of the load from the fixed extremity.

### STRENGTHS, ETC., OF BEAMS.

30. The moment of the forces tending to rupture a beam being always equal to the moment of the forces resisting rupture, the symbol M may be used to express either of these moments. It must be observed, therefore, that all the expressions hereafter given for M, the moment of rupture or the moment of flexure, as the case may be, are equal to the moment of the forces tending to break the beam.

31. One of the leading practical problems to be solved in relation to the strength of material is this: Given the moment of the greatest load, M, tending to rupture a proposed beam, to find the strain per square inch of the material at the weakest part of the transverse section of the beam. For this purpose, from eq. (9), Art. 11, we get

$$s = \frac{M h}{I_0}, \text{ or } s_1 = \frac{M h_1}{I_0} \quad \ldots \quad (1)$$

In order that the beam may support this load permanently, or without sustaining injury in its structure, the value of s or $s_1$, as the case may be, determined from this equality, should not exceed one-third the ultimate value of s or $s_1$, that is, in the case of wrought iron, the tensile strain per square inch should not exceed one-third of 21 tons, or 7 tons, and the compressive strain should not exceed 6 tons.

The values of M, under various conditions, have been determined in the foregoing section; and it now remains for us to determine the values of $I_0$ for the various forms and dimensions of the transverse sections of beams.

Digitized by Google

WHEN THE NEUTRAL AXIS PASSES THROUGH THE CENTRE OF THE SECTION.

32. Let A B C D (see fig. 108) be *a solid rectangle,* in which the neutral axis K G passes through the centre of the section; $b$ = A B, the breadth of the beam; $d$ = A D, the depth, and $h = h_1 = \frac{d}{2}$, then by eq. (5), Art. 10, the moment of inertia of the rectangle A B K G is $\frac{1}{3} b h^3$, but the moment of the solid rectangle A B C D is double this,

$$\therefore I_0 = \frac{2}{3} b h^3 = \frac{2}{3} b \left(\frac{d}{2}\right)^3 = \frac{1}{12} b d^3 \ \ldots \ (1)$$

Or putting K for the area of the section,

$$I_0 = \frac{1}{12} K d^2 \ \ldots \ (2)$$

which is the moment of inertia of a solid rectangle about an axis passing through its centre of gravity, and parallel to the upper and under edges of the section.

Also,

$$M = \frac{S}{h} I_0 = \frac{1}{6} S b d^2 \ \ldots \ (3)$$

where *the strength of the beam varies as the square of its depth.*

Or substituting K for $b d$,

$$M = \frac{1}{6} S d K \ \ldots \ (4)$$

where *the strength varies as the product of the depth and the sectional area.*

When the beam is upon the point of rupture, putting C for the constant $\frac{1}{6}$ S, we get

$$M = C b d^2 \ \ldots \ (5)$$

where the constant C, determined by experiment for the proposed material, has been called *the modulus of ultimate strength.* The value of this constant for different kinds of material may be found in tables based upon the results of experiment. When the beam is supported at the extremities and loaded in the middle (fig. 99), Art. 9, $M = \frac{W l}{4}$, where $l$ is

Digitized by Google

the distance between the supports; in this case eq. (5) becomes

$$\frac{w\,l}{4} = c\,b\,d^2, \therefore w = \frac{4\,c\,b\,d^2}{l} \quad \ldots (6)$$

where $b$, $d$, and $l$ are in units of inches, and w will be in the same unit of weight as c. Moreover, we have

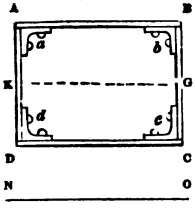
$$c = \frac{w\,l}{4\,b\,d^2} \quad \ldots (7)$$

which gives the value of c, the modulus of strength, w being determined by experiment for a given rectangular beam. This value of c is sometimes called *the unit of strength.*

*Hollow Rectangular Beams, and Beams with Double Flanges.*

33. Let A B C D be the transverse section of a hollow rectangular beam of uniform thickness:

Fig. 108.




$d$ = A D, the depth of the beam;

$h = h_1 = \frac{d}{2}$, the neutral axis K G passing through the centre of the section;

$d_1 = a\,d$, the interior depth;

$b_1$ = the interior breadth; $I_0$ = the moment of inertia of the whole section; and so on.

Here, $I_0$ = moment inertia A B C D − moment inertia $a\,b\,c\,d$; hence we have by eq. (1), Art. 32,

$$I_0 = \frac{1}{12}\,b\,d^3 - \frac{1}{12}\,b_1\,d_1^3 = \frac{1}{12}\,(b\,d^3 - b_1\,d_1^3) \quad \ldots (1)$$

When $b = d$, and $b_1 = d_1$, or when the section is a square,

$$I_0 = \frac{1}{12}\,(d^4 - d_1^4) = \frac{1}{12}\,(d^2 - d_1^2)\,(d^2 + d_1^2)$$

$$= \frac{1}{12}\,K\,(d^2 + d_1^2) \quad \ldots (2)$$

And for the moment of rupture M of the hollow beam, we have

$$M = s\,I_0 = \frac{S}{\frac{1}{2}\,d}\,I_0 = \frac{S}{6\,d}\,(b\,d^3 - b_1\,d_1^3) \quad \ldots (3)$$

And when the beam is square,

$$M = \frac{S\,K}{6\,d}\,(d^3 + d_1^3) \quad \ldots (4)$$

Digitized by Google

If the thickness of the plates be comparatively small, then $\frac{d_1}{d} = 1$ nearly, and

$$M = \frac{1}{3} S K d \quad \ldots (5)$$

where *the strength varies as the area of the section multiplied by the depth.*

Eq. (3) also gives the moment of rupture of a beam with a double flange, K being the area of the section of the material, $d$ the depth, and $d_1$ the length of the rib.

34. When the box beam has *angle-iron* at the corners, secured by rivets. Let $c$ = the length of each angle-iron, $t$ = their thickness, and $v_2$ = their moment of inertia about the neutral axis K G passing through the centre of the beam; then by eq. (1), Art. 32, we get

$$v_2 = \tfrac{1}{6}\{c\,d_1^3 - t\,(d_1 - 2\,c)^3 - (c-t)\,(d_1 - 2\,t)^3\} \quad \ldots (6)$$

In order to make allowance for the material cut out by the rivets, let $v_3$ = the moment of inertia of the material cut out; $k = \frac{1}{2}(b - b_1)$, the thickness of each vertical plate; $\delta$ = the diameter of the rivet hole, there being two rivets in each angle-iron, one passing through the horizontal plate, and one through the vertical plate, $\delta_1$ being put for the distance of the centre of the latter from K G; then

$$v_3 = \frac{1}{6}\left[\delta\{d^3 - (d_1 - 2t)^3\} + (k+t)\{(2\delta_1 + \delta)^3 - (2\delta_1 - \delta)^3\}\right] \ldots (7)$$

$$= \frac{\delta}{6}\{d^3 - (d_1 - 2\,t)^3 + 24\,(k+t)\,\delta_1^2\},$$

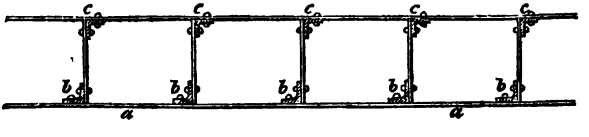
when $\delta$ is small as compared with $\delta_1$.

Now putting $v_1$ for the expression given in eq. (1) and $I_0$ for the moment of inertia of the beam taking the angle-iron and rivet holes into the calculation, we have, by collecting the results of eq. (1), (6), and (7),

$$I_0 = v_1 + v_2 - v_3 \quad \ldots (8)$$

35. When the beam is composed of *a series of cells* as described in Art. 12, Chap. VI. Let $n$ be the number of vertical

Fig. 109.




S

Digitized by Google

plates, $k$ being the thickness of each, and $b$ the whole breadth of the beam; then

The moment of inertia of the horizontal and vertical plates will be found from eq. (1) by substituting $(b-n\,k)$ for $b_1$; the moment of inertia of the angle-iron will be $n$ times $\frac{1}{2}\,v_2$; and that of the rivet holes $n$ times $\frac{1}{2}\,v_3$; hence, in this case, we have

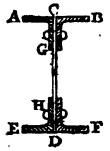
$$I_0 = \frac{1}{12}\left\{ b\,d^3 - (b-n\,k)\,d_1^{\,3} \right\} + \frac{n}{2}(v_2 - v_3) \quad \ldots \quad (9)$$

where $v_2$ and $v_3$ are given in eq. (6) and (7).

36. Comparative strength of solid and hollow beams, having the same depth and section of material.

Subtracting eq. (4) Art. 32, from eq. (4) Art. 33, we find $\frac{S\,K\,d_1^{\,2}}{6\,d}$ for the excess of strength of the latter over the former. When the plates composing the hollow beam are thin, $\frac{d_1}{d} = 1$ nearly, and then the hollow beam will have double the strength of the solid one.

Fig. 110.




37. A beam of wrought iron is composed of a uniform rib, with two angle-irons, of the same dimensions, riveted to both the top and the bottom of the rib.

Adopting the foregoing notation, $d_1$ being, in this case, the depth of the beam, and $k$ the thickness of the rib, we get

$$I_0 = \frac{1}{12}\left\{ (2c+k)d_1^{\,3} - 2(c-t)(d_1-2t)^3 - 2t(d_1-2c)^3 \right\} - v \quad \ldots (1)$$

where $v$ is put for the moment of inertia of the material cut out by the rivet holes, which is expressed by

$$v = \frac{1}{12}(k+2\,t)\left\{(2\,\delta_1+\delta)^3 - (2\,\delta_1-\delta)^3\right\} \quad \ldots \quad (2)$$

$$= 2\,(k+2\,t)\,\delta_1^{\,2}\,\delta,$$

when $\delta$ is small as compared with $\delta_1$.

### CYLINDRICAL BEAMS.

38. Let END M be the transverse section of a cylindrical beam, fig. 111, MN the diameter, and O the centre of the circle. Let $r$ = the radius, $x = $ O $m$, $y = $ A $m$; then from the equation to the circle

$$y = (r^2 - x^2)^{\frac{1}{2}},$$

$$\therefore\ y^3 = (r^2 - x^2)^{\frac{3}{2}},$$

Digitized by Google

and substituting in eq. (7), Art. 10, we get

$$I = \frac{1}{3}\int_0^r (r^2 - x^2)^{\frac{3}{2}}\, dx = \frac{1}{16}\pi r^4,$$

(See Tate's 'Calculus,' Ex. 6, p. 183), which is the moment of inertia of the quadrant O N E. Therefore the moment of inertia of the whole circle about its diameter will be

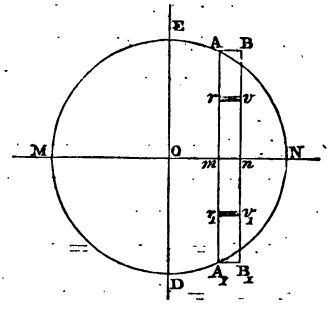


Fig. 111.

$$I_0 = \tfrac{1}{4}\pi r^4 \quad \ldots \quad (1)$$

but the area of the section, $K = \pi r^2$,

$$\therefore I_0 = \tfrac{1}{4} K r^2,$$

$$\therefore M = \frac{S}{r} I_0 = \tfrac{1}{4} S K r \quad \ldots \quad (2)$$

If the beam be supported at the ends and loaded in the middle, then

$$W = \frac{4M}{l} = \frac{S}{2} \cdot \frac{K d}{l} \quad \ldots \quad (3)$$

That is, *the breaking weight of a solid cylindrical beam is equal to the continued product of the sectional area, the depth, and a constant,* $\frac{S}{2}$, *divided by the distance between the supports.*

39. When the beam is *a hollow cylinder,* whose internal diameter is $d_1$, then the moment of inertia will be equal to the difference of the moments of the two circles. Hence we have from eq. (1)

$$I_0 = \frac{\pi}{64}(d^4 - d_1^4) = \frac{\pi}{64}(d^2 - d_1^2)(d^2 + d_1^2)$$

$$= \frac{K}{16}(d^2 + d_1^2) \quad \ldots \quad (4)$$

and $$M = \frac{S}{r} I_0 = \frac{S}{8} \cdot \frac{K}{d}(d^2 + d_1^2) \quad \ldots \quad (5)$$

40. When the thickness of the plate forming the hollow cylinder is small as compared with the diameter, $\frac{d_1}{d} = 1$ very nearly, then eq. (5) becomes

$$M = \frac{S}{8} \cdot K d\left(1 + \frac{d_1^2}{d^2}\right) = \frac{S}{4} \cdot K d, \text{ nearly} \quad \ldots \quad (6)$$

When $M = \frac{W l}{4}$, then we get



Digitized by Google

$$W = \frac{S K d}{l} \quad \ldots (7)$$

The mean value of S, determined from Dr. Fairbairn's experiments, is $14\frac{1}{2}$ tons. Hence, *the breaking weight, in tons, is equal to the continued product of the sectional area, the depth, and a constant,* $14\frac{1}{2}$, *divided by the distance between the supports.*

41. To find the moment of inertia, $I_0$, of a semicircle, M N E, about an axis passing through its centre of gravity parallel to the diameter M N.

Put $I_x = \frac{1}{8} \pi r^4$ = moment inertia about N M, by eq. (1);

$e = \frac{4 r}{3 \pi}$ = the distance of the centre of gravity from N M;

then by eq. (2) Art. 13, we have

$$I_0 = I_x - K e^2 = r^4 \left( \frac{\pi}{8} - \frac{8}{9 \pi} \right) = \cdot 11 r^4 \text{ nearly} \quad \ldots (8)$$

42. To find the moment of inertia, $I_{x_1}$, of a semicircle about any axis N O parallel to the diameter M N.

Let $e_1$ = the distance of the axis N O from M N; and therefore $e_1 + e$ will be its distance from the centre of gravity of the semicircle; hence we get by Art. 13,

$$I_{x_1} = I_x + \tfrac{1}{2} \pi r^2 \{ (e_1 + e)^2 - e^2 \} = I_x + \tfrac{1}{2} \pi r^2 e_1 (e_1 + 2 e)$$
$$= \tfrac{1}{8} \pi r^2 (r^2 + 4 e_1^2) + \tfrac{4}{3} e_1 r^3 \quad \ldots (9)$$

When M E N is a semicircular plate whose exterior radius is $r$, and interior radius $r^1$, its moment of inertia will be expressed by $I_{x_1} - I^1_{x_1}$, where $I^1_{x_1}$ is derived from $I_{x_1}$, given in eq. (9), by putting $r^1$ in the place of $r$. The moment of inertia of a plate, whose thickness is $r - r^1$, having the form of a quadrant, will be one-half this expression.

43. To determine the comparative strengths of a hollow cylindrical beam and a hollow square beam, having the same sectional area and diameter.

From eq. (6) Art. 39, and eq. (5) Art. 33, we have

$$\frac{M}{M_1} = \frac{\frac{1}{6} S K d}{\frac{1}{4} S K d} = \frac{4}{3} \quad \ldots (1)$$

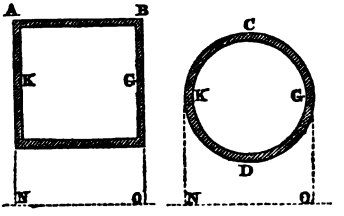
that is to say, with the same material the square beam is $1\frac{1}{3}$ times the strength of the cylindrical one.

44. To determine the comparative strengths of circular and square cells, forming portions of a girder.

Digitized by Google

Let C D be a circular cell, and A B a square one, having the areas of the sections the same, the diameter C D = the side A B = $d$, and the lines K G, passing through the centres, at the same distance, $\bar{x}$, from the axis of moments N O.

Fig. 112.




For the circular cell we have, by eq. (1) Art. 13, and eq. (4) Art. 39.

$$M_1 = s I_x = s (I_0 + \bar{x}^2 K) = \frac{s K}{16}(d^2 + d_1^2 + 16 x^2)$$

$$= \frac{s K}{8}(d^2 + 8 \bar{x}^2), \text{ very nearly } \ldots (1)$$

Similarly for the square cell, by eq. (2), Art. 33, we find

$$M = \frac{s K}{6}(d^2 + 6 \bar{x}^2) \text{ very nearly } \ldots (2)$$

Taking the difference of (1) and (2), we get

$$M - M_1 = \frac{1}{24} s K d^2$$

$$\text{When } \bar{x} = d, \frac{M}{M_1} = 1\tfrac{1}{27}$$

Hence it appears that the square cell is stronger than the circular one.

*Elliptical Beams.*

45. Let E N D M be the transverse section of an elliptical beam (see fig. 111); O N the semi-minor diameter, and O E the semi-major diameter. Let $b$ = O N = O M, $a$ = O E = O D, $x$ = O $m$, $y$ = A $m$; then $y = \frac{a}{b}(b^2 - x^2)^{\frac{1}{2}}$, and by substitution in eq. (7) Art. 10,

$$I = \frac{1}{3} \cdot \frac{a^3}{b^3} \int_0^b (b^2 - x^2)^{\frac{3}{2}} dx = \frac{1}{16} \pi b a^3,$$

which expresses the moment of inertia of the quadrant N O E; hence the moment of inertia of the whole ellipse about its minor diameter will be

$$I_0 = \tfrac{1}{4} \pi b a^3 = \tfrac{1}{4} K a^2 \ldots (1)$$

where K is put for $\pi a b$ the area of the section.

$$\therefore M = \frac{S}{a} \cdot I_0 = \tfrac{1}{4} S K a = \tfrac{1}{8} S K d \ldots (2)$$

Digitized by Google

When the beam is supported at the extremities and loaded in the middle,

$$W = \frac{4\,M}{l} = \frac{S}{2} \cdot \frac{K\,d}{l} \quad \ldots (3)$$

which is the same expression as that given in eq. (3) Art. 38, for cylindrical beams.

46. *A hollow elliptical beam.* Putting $a_1$ and $b_1$ for the semi-axes of the interior ellipse, we have from eq. (1)

$$I_0 = \frac{\pi}{4}(b\,a^3 - b_1\,a_1^3)$$

$$\therefore M = \frac{S\,\pi}{4\,a}(b\,a^3 - b_1\,a_1^3) \quad \ldots (4)$$

When $\frac{a}{b} = \frac{a_1}{b_1}$, by an obvious reduction, we get

$$M = \frac{S\,\pi}{4\,b}(b^2\,a^2 - b_1^2\,a_1^2) = \frac{S\,K\,a}{4}\left(1 + \frac{b_1\,a_1}{b\,a}\right)$$

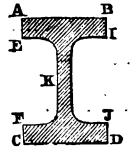
$$= \tfrac{1}{2}\,S\,K\,a \text{ or } \tfrac{1}{4}\,S\,K\,d \quad \ldots (5)$$

by taking $\frac{b_1\,a_1}{b\,a} = 1$, which it is nearly when $b_1$ is nearly equal to $b$.

This expression is the same as that given, eq. 6, Art. 39, for hollow cylindrical beams. The mean value of S, determined from Dr. Fairbairn's experiments, is 15 tons.

47. To determine the strength of a beam having a rectangular section, A B C D, and *hollowed at the sides by the semi-ellipses* E K F and I K J.

Fig. 113.




Let $b$ = A B = C D; $d$ = A C = B D; $a_1 = \frac{1}{2}$ E F, the semi-major diameter of the ellipse; $b_1$ = the semi-minor diameter; then taking the moments of inertia about the neutral axis passing through the centre, we have

Moment inertia rectangle A B D C $= \frac{1}{1\cdot 2}\,K\,d^2$

Moment inertia ellipse $= \frac{1}{4}\,K_1\,a_1^2$

$$\therefore I_0 = \tfrac{1}{12}\,K\,d^2 - \tfrac{1}{4}\,K_1\,a_1^2 \quad \ldots (1)$$

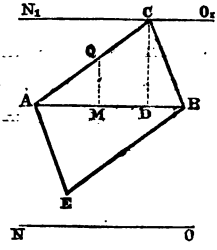
## OBLIQUE LINED BEAMS.

48. To determine *the moment of inertia,* $q_1$, *of a triangle* A B C *about its base* A B.

Digitized by Google

Let $a$ = C D, the perpendicular on A B; $e$ = A D; $e_1$ = D B; $b$ = A B; $x$ = A M; $y$ = M Q;

Fig. 114.




then $y = \frac{a x}{e}$; and substituting in eq. (6), Art. 10, we get

Moment inertia triangle A D C $= \frac{1}{3}\int_0^e y^3\, dx$

$$= \frac{a^3}{3\,e^3}\int_0^e x^3\, dx = \tfrac{1}{12}\, e\, a^3$$

In like manner we find the moment of inertia of the triangle D B C $= \frac{1}{12}\, e_1\, a^3$.

Now the moment of inertia of the whole triangle will be equal to the sum of these two;

$$\therefore q_1 = \tfrac{1}{12}\, e\, a^3 + \tfrac{1}{12}\, e_1\, a^3 = \tfrac{1}{12}\, b\, a^3 \ \ldots\ (1)$$

Putting K for the area of the triangle, we also have

$$q_1 = \tfrac{1}{6}\, \mathrm{K}\, a^2 \ \ldots\ (2)$$

49. To determine the moment of inertia, $q_0$, of the triangle, A B C, *about an axis passing through its centre of gravity and parallel to the base* A B.

The distance of the centre of gravity from the base is $\frac{1}{3}\, a$; therefore by substituting $\frac{1}{3}\, a$ for $\bar{x}$ in eq. (2), Art. 13, we get

$$q_0 = q_1 - \tfrac{1}{2}\, a\, b \times \left(\frac{a}{3}\right)^2 = \frac{1}{36}\, b\, a^3 \text{ or } \frac{1}{18}\, \mathrm{K}\, a^2 \ \ldots\ (3)$$

Comparing this with eq. (1), we find

$$q_1 = 3\, q_0 \ \ldots\ (4)$$

50. To determine the moment of inertia, $\mathrm{I}_x$, of the triangle, A B C, *about any axis*, N O, *parallel to the base* A B, at the distance $\bar{x}$ from the centre of gravity of the triangle.

By eq. (1), Art. 13,

$$\mathrm{I}_x = q_0 + \bar{x}^2\, \mathrm{K} = \mathrm{K}\left(\tfrac{1}{18}\, a^2 + \bar{x}^2\right) \ldots\ (5)$$

1. If the axis be $\mathrm{N}_1\, \mathrm{O}_1$, *passing through the vertex*, then $\bar{x} = \frac{2}{3}\, a$, and putting $q_2$ for the resulting value of $\mathrm{I}_x$, this equality becomes

$$q_2 = \mathrm{K}\left(\tfrac{1}{18}\, a^2 + \tfrac{4}{9}\, a^2\right) = \tfrac{1}{2}\, \mathrm{K}\, a^2 \ \ldots\ (6)$$

$$\therefore q_2 = 9\, q_0 \text{ or } 3\, q_1 \ \ldots\ (6)$$

51. *To find the moment of inertia*, $\mathrm{I}_0$, *of a parallelogram*, A C B E, *about its diagonal* A B, we have, by doubling eq. (2),

$$\mathrm{I}_0 = \tfrac{1}{3}\, \mathrm{K}\, a^2 \ \ldots\ (7)$$

$$\therefore \mathrm{M} = \frac{\mathrm{S}}{a} \cdot \mathrm{I}_0 = \tfrac{1}{3}\, \mathrm{S}\, \mathrm{K}\, a \ \ldots\ (8)$$

Digitized by Google

Or putting $d$ for the whole vertical depth of the beam,

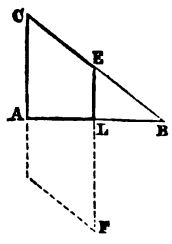
$$M = \tfrac{1}{6} S d K \quad \ldots \quad (9)$$

which is the same expression as that given for rectangular beams. See eq. (4), Art. 32.

1. When A C = C B = A B = $a_1$, then $a^2 = \frac{3}{4} a_1^2$, and eq. (7) becomes

$$I_0 = \tfrac{1}{4} K a_1^2 \quad \ldots \quad (10)$$

Fig. 115.




52. To find the moment of inertia, I, of *a trapezoid*, A C E L, about the base, A L, perpendicular to the parallel sides.

Let $a$ = A C, $a_1$ = L E, $c$ = A L, $b$ = A B, $b_1$ = L B; then by eq. (1), Art. 48, the moment of inertia of the triangle, A B C, is $\frac{1}{12} b a^3$, and that of L B E is $\frac{1}{12} b_1 a_1^3$;

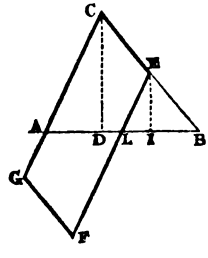
$$\therefore I = \frac{1}{12}(b a^3 - b_1 a_1^3) = \frac{1}{12}\frac{b}{a}(a^4 - a_1^4)$$

$$= \frac{1}{12}\frac{c}{a - a_1}(a - a_1)(a + a_1)(a^2 + a_1^2) = \tfrac{1}{6} K (a^2 + a_1^2) \quad \ldots \quad (1)$$

This will also express the moment of inertia of the parallelogram, C F, the axis of moments passing through the centre.

53. *To find the moment of inertia of a parallelogram* C E F G, *about any axis*, A B, *passing through its centre.*

Fig. 116.




Let $a$, $a_1$ = C D, E I, respectively, perpendiculars on A B; $b$ = A B, $b_1$ = L B, $\theta$ = ∠ C, $\theta_1$ = ∠ B, the angle which the axis makes with the side C E; $l$ = C G; $e$ = C E; then we find as in the foregoing investigation,

$$I_0 = \frac{1}{6}\frac{b}{a}(a^4 - a_1^4) \quad \ldots \quad (1)$$

By the property of similar triangles, and the substitution of trigonometrical values, we finally obtain

$$I_0 = \tfrac{1}{12} K \{l^2 \sin^2(\theta_1 + \theta) + e^2 \sin^2 \theta_1\} \quad \ldots \quad (2)$$

1. To determine the position of the axis, or the value of $\theta_1$, when $I_0$ is a maximum. By differentiation, &c., we get $\frac{\sin 2(\theta_1 + \theta)}{\sin 2\theta_1} = \frac{e^2}{l^2}$, whence we find,

$$\tan 2\theta_1 = \frac{l^2 \sin 2\theta}{e^2 + l^2 \cos 2\theta} \quad \ldots \quad (3)$$

Digitized by Google

When $\theta = 90°$, tan 2 $\theta_1 = 0$, and $\therefore \theta_1 = 0$, that is, the axis is parallel to the side C E, or perpendicular to C G.

54. *When the axis* A L *is perpendicular to the side* C G, $\theta_1 = 90 - \theta$, sin $\theta_1 = \cos \theta$, and sin $(\theta_1 + \theta) = 1$; then eq. (2) becomes

$$I_0 = \tfrac{1}{12} K (l^2 + e^2 \cos^2 \theta) \quad \ldots \quad (4)$$

55. When $\theta = 90°$, or the surface becomes a *rectangle*, sin $(\theta_1 + \theta) = \cos \theta_1$, and then eq. (2) becomes

$$I_0 = \tfrac{1}{12} K (l^2 \cos^2 \theta_1 + e^2 \sin^2 \theta_1) \quad \ldots \quad (5)$$

which expresses the *moment of inertia of a rectangle about an oblique axis* A L.

1. When $e = l$, that is, when the surface becomes *a square*, $\cos^2 \theta_1 + \sin^2 \theta_1 = 1$, and then eq. (5) becomes

$$I_0 = \tfrac{1}{12} K l^2 = \tfrac{1}{12} l^4 \quad \ldots \quad (6)$$

which being independent of $\theta_1$, we have the following remarkable property :—

Property of the square. *The moment of inertia of a square is the same for all axes passing through the centre, whatever may be their inclination.* This property is not limited to the square.

2. When the rectangle is the section of a thin plate, by neglecting $e$, eq. (5) becomes

$$I_0 = \tfrac{1}{12} K l^2 \cos^2 \theta_1 \quad \ldots \quad (7)$$

where $l \cos \theta_1$ is the projection of $l$, the length of the plate, upon the vertical.

56. Let C E F G (fig. 116), represent the section of a *box girder*, or of a double-flanged beam, the top and bottom plates being equal. To find the moment of inertia *about any axis passing through the centre of the section.*

Put $l_1$, $e_1$, $K_1$ for the internal dimensions of the sections, all the other symbols being the same as those of eq. (5). By eq. (5) and by subtracting the moment of inertia of the internal rectangle from that of the external one, we get

$$I_0 = \tfrac{1}{12} \{(K l^2 - K_1 l_1^2) \cos \theta_1 + (K e^2 - K_1 e_1^2) \sin^2 \theta_1\} \quad \ldots \quad (8)$$

When $e = l$, $e_1 = l_1$, then this equality becomes

$$I_0 = \tfrac{1}{12} (K l^2 - K_1 l_1^2) \quad \ldots \quad (9)$$

which being independent of $\theta_1$ shows that *the moment of inertia of a square hollow girder is the same for all axes passing through the centre, whatever may be their inclination.*

Digitized by Google

57. If we put A and B for the moments of inertia of the rectangle, eq. (5), about the principal axes perpendicular to $l$ and $e$, then this equation becomes

$$I_0 = A\cos^2\theta_1 + B\sin^2\theta_1 \quad \ldots \quad (10)$$

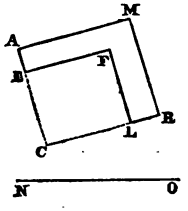
where $\theta_1$ is the inclination of the oblique axis to the principal axis corresponding to the moment of inertia A.

It may be shown that this formula holds true for all forms of section having two principal axes perpendicular to each other.

58. To *find the moment of inertia of the angle-iron*, A M R E, *about the axis* N O *having any assigned position.*

Let $l$ = A M = M R, the side of the square M C; $l_1$ = E F = F L, the side of the square F C; $\bar{x}$, $\bar{x}_1$ = the distances of the centres of the squares M C and F C respectively from N O.

Fig. 117.




The moment of inertia of the material in the section of the angle-iron will be equal to the difference of the moments of inertia of the two squares; hence we have

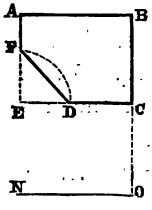
$$I_x = \frac{1}{12}(l^4 - l_1^4) + l^2\bar{x}^2 - l_1^2\bar{x}_1^2 \quad \ldots \quad (11)$$

1. When A M is parallel to N O, and if $c$ be put for the distance of the edge L R from N O, then in the foregoing equality we have $\bar{x} = c \pm \frac{l}{2}$, and $\bar{x}_1 = c \pm \frac{l_1}{2}$. If, in this case, $c$ = 0, then

$$I_x = \tfrac{1}{3}(l^4 - l_1^4) \quad \ldots (12)$$

59. To find the moment of inertia, $I_x$, of *a rectangle*, A B C E, *having a corner*, F E D, *cut off, about the axis* N O *parallel to* A B.

Fig. 118.




Let $l$ = A B; $c$ = B C; $a$ = F E; $b$ = E D; $e$ = O C.

Now, the moment of inertia of A B C E about its centre of gravity is $\frac{1}{12} l c^3$, and that of the triangle F E D is $\frac{1}{36} b a^3$; hence we have by eq. (1) Art. 13,

$$I_x = \frac{1}{12} l c^3 - \frac{1}{36} b a^3 + l c\left(e + \frac{c}{2}\right)^2 - \tfrac{1}{2} a b (e + \tfrac{1}{3} a)^2 \ldots (13)$$

If the corner cut off be a *quadrant* of a circle, radius $r$, then

Digitized by Google

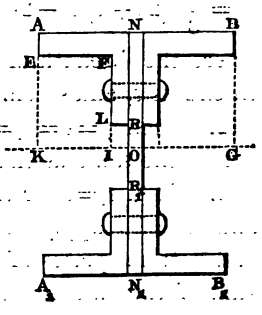
the moment of inertia of this quadrant will be $\frac{1}{2} I_{x_1}$ see eq. (9), Art. 42; in this case, therefore, we have

$$I_x = \frac{1}{12} l c^3 + l c \left(e + \frac{c}{2}\right)^2 - \frac{1}{2} I_{x_1} \quad \ldots (14)$$

WHEN THE NEUTRAL AXIS DOES NOT PASS THROUGH THE CENTRE OF THE SECTION.

60. A girder, A B $A_1$, $B_1$, is composed of an uniform rib, N $N_1$, with two angle-irons riveted to the top and two to the bottom of the rib.

Fig. 119.




Let $e$ = A N, the breadth of the angle-iron at the top; $c$ = N R, its depth; $t$ = A E = L R, the thickness; $h$ = A K = B G, the distance of the neutral axis from the edge A B; $\delta$ = the diameter of the rivet hole, $q$ being the distance of its centre from A B; and so on to these symbols accented for the corresponding parts of the section below the neutral axis. Moreover, let $d$ = N $N_1$, the depth of the girder; $k$ = the thickness of the rib N $N_1$; K = the area of the section of the material.

For the neutral axis, we have by Art. 8, taking A B as the axis of moments,

$$h = \frac{1}{K}\{(e-t)\,t^2 + t\,c^2 + t_1(e_1-t_1)(2\,d-t_1) + t_1 c_1 (2\,d-c_1) + \tfrac{1}{2}\,k\,d^2 - \delta\,(2\,t+k)\,q - \delta_1\,(2\,t_1+k)\,(d-q_1)\} \quad \ldots (1)$$

The value of $h$ being found, we have $h_1 = d - h$.

The moment of inertia of the section of the material above K G, or I = moment inertia rectangle A B G K − 2 $c$ $e$ moment inertia rectangle E F I K − 2 $c$ $e$ moment inertia rectangle L R O I − moment inertia rivet hole. Hence we find

$$I = \frac{1}{3}\Big[(2\,e+k)\,h^3 - 2\{(e-t)(h-t)^3 + t(h-c)^3\} - (2\,t+k)\{3\,(h-q)^2\delta + \frac{\delta^3}{4}\}\Big] \quad \ldots (2)$$

The value of $I_1$ or the moment of inertia of the material below the neutral axis is obtained from (2) by merely placing

Digitized by Google

accents to the symbols $h$, $e$, $c$, $t$, $q$, and $\delta$. Hence we have for the moment of inertia of the whole section

$$I_0 = I + I_1 \quad \ldots (3)$$

$$\therefore M = s I_0 = \frac{s}{h}(I + I_1) \text{ or } \frac{s_1}{h_1}(I + I_1) \quad \ldots (4)$$

1. When $c = t$, $c_1 = t_1$, the section is that of *a beam with double unequal flanges*; then, neglecting the rivet holes, eq. (1) and (3) become

$$h = \frac{1}{K}\{e t^2 + e_1 t_1 (2 d - t_1) + \tfrac{1}{2} k d^2\} \quad \ldots (5)$$

$$I_0 = \frac{1}{3}\{(2e+k)h^3 - 2e(h-t)^3 + (2e_1+k)h_1^3 - 2e_1(h_1-t_1)^3\} \quad \ldots (6)$$

where the breadth, A B, of the top flange is $(2e+k)$, and its thickness $t$, and so on.

2. When $e_1 = e = c_1 = c$, and $t_1 = t$, in eq. (3), the section becomes the same as that of Art. 37.

3. When $e_1 = e$, or the flanges are of the same length, eq. (5) and (6) also apply to a hollow beam, fig. 10, having the top and bottom plates of unequal thickness, viz., $t$ and $t_1$, and the sum of the thicknesses of the side plates $k$. And if we further take $t_1 = t$, the resulting expression for $I_0$ gives the moment of inertia of a simple hollow beam, as in eq. (1) Art. 33.

61. *To find the moment of inertia,* $I_x$, *of the system of rectangular cells,* described in Art. 35, about any axis N O parallel to K G the neutral axis of the cells. See fig. 108.

Here the moment of inertia, $I_0$, of these cells about their neutral axis is given in eq. (9) Art. 35; putting $\bar{x} = K N = G O$, we have, by eq. (1) Art. 13,

$$I_x = I_0 + x^2 K \quad \ldots (1)$$

62. *To find, approximately, the moment of inertia,* I', *of a system of rectangular cells,* A B C D, *forming a portion of the section of a beam,* about the neutral axis, N O, of the beam, parallel to the edge A B or C D. See fig. 108.

Suppose the whole of the vertical plates to be collected in the two side plates A D and B C; and let $b = A B$, the exterior breadth; $b_1 = a\,b$, the interior breadth; $e = A D = B C$, the exterior depth; $e_1 = a\,d = b\,c$, the interior depth; $g = K N = G O$, the distance between the two axes N O and K G; $a =$ the section of the material; then

Digitized by Google

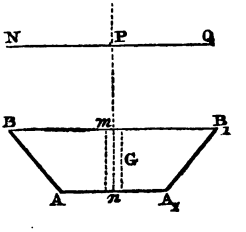
$$I' = \frac{b}{3}\left\{\left(g+\frac{e}{2}\right)^3-\left(g-\frac{e}{2}\right)^3\right\}-\frac{b_1}{3}\left\{\left((g+\frac{e_1}{2}\right)^3-\left(g-\frac{e_1}{2}\right)^3\right\}$$
$$=(b\,e-b_1\,e_1)\,g^2 = a\,g^2 \ \ldots\ (1)$$

where the terms $\frac{e^2}{12g^2}$ and $\frac{e_1^2}{12g^2}$ are neglected, being very small as compared with unity.

Hence it appears that *the moment of inertia of the system is equal to the area of the section multiplied by the square of the distance of the centre of gravity from the neutral axis.*

63. *Two equal plates,* A B, $A_1$ $B_1$, *forming a portion of a beam,* having the same inclination; to find their moment of inertia about the neutral axis, NO, parallel to A $A_1$ or B $B_1$.

Fig. 120.




Let $a$ = the area section of the two plates; $g$ = G P, the distance of their centre of gravity from N O; $e = n\ m$, the projection of the plates on the vertical $n$ P.

Here (by eq. (7) Art. 55) the resistance of the plates will be equivalent to the resistance of the rectangle $n\ m$ whose base is equal to $\frac{a}{e}$; hence we have

$$I = \frac{a}{3e}\left\{\left(g+\frac{e}{2}\right)-\left(g-\frac{e}{2}\right)^3\right\} = \frac{a}{3e}\left\{3g^2e+\frac{e^3}{4}\right\} = g^2a,$$

very nearly, which is the same result as that given in the foregoing article.

*To find the moment of inertia of a complex girder, such as an iron ship, composed of a series of parts.*

64. Let $a_0$, $a_1$, . . . $a_n$ represent the sectional areas of the portions composing the transverse section of the beam; $\alpha_0$, $\alpha_1$, . . . $\alpha_n$ the distance of the centres of gravity of these areas respectively from the upper edge A B of the section; $Q_0$, $Q_1$, . . . $Q_n$ the moments of inertia of these areas respectively about their respective centres of gravity; $h$ the distance of the neutral axis of the whole section from the upper edge.

For the neutral axis we have

$$h = \frac{a_0\,\alpha_0 + a_1\,\alpha_1 + \ldots + a_n\,\alpha_n}{a_0 + a_1 + \ldots + a_n} = \frac{1}{K}\,\Sigma_0^n\, a_n\,\alpha_n \ \ldots\ (1)$$

Digitized by Google

The distance of the centre of gravity of the area $a_n$ from the neutral axis is $(h-\alpha_n)$, and so on to the others; hence we have from eq. (1), Art. 13,

$$I_0 = Q_0 + Q_1 + \ldots + Q_n + a_0(h-\alpha_0)^2 + a_1(h-\alpha_1)^2 + \ldots + a_n(h-\alpha_n)^2$$
$$= \Sigma_0^n Q_n + \Sigma_0^n a_n (h-\alpha_n)^2 \quad \ldots \quad (2)$$

where it will be observed that $(h-a_n)^2$ is always positive.

Hence we have the following general theorem:

*General Theorem.* I. If the section of a compound girder be composed of a series of sectional areas, the moment of inertia of the whole section, about its neutral axis, is equal to the sum of the moments of inertia of the different sections about their respective centres of gravity added to the sum of all the areas multiplied respectively by the square of the distance of their centres of gravity from the neutral axis.

N.B.—It may happen that the moment of inertia, $Q_r$, of some part of the section can be most readily found by referring at once to the neutral axis, N O, of the whole section; then, in this case, the value of $Q_r$ must be added to eq. (2).

65. If $Q_0$, $Q_1$ be taken as the moments of inertia of the sectional areas which meet or pass through the line of the neutral axis, or which may have a considerable depth, as for example the side plates of a tubular girder; and supposing the other sectional areas to be accumulated towards the upper and lower parts of the section of the beam; then the depths of these sectional areas being small as compared with their respective distances from the neutral axis; $Q_2, \ldots, Q_n$ may be neglected without incurring any considerable error.

$$\therefore I_0 = Q_0 + Q_1 + \Sigma_0^n a_n (h-\alpha_n)^2 \quad \ldots \quad (3)$$

And if $Q_0$, $Q_1$ be neglected, then

$$I_0 = \Sigma_0^n a_n (h-\alpha_n)^2 \quad \ldots \quad (4)$$

Hence we have the following general theorem:

*General Theorem.* II. When the different depths of the sectional areas of a series of plates, forming a compound girder, are small as compared with the distance of their respective centres of gravity from the neutral axis, then the moment of inertia of the whole section is very nearly equal to the sum of all the areas multiplied respectively by the square of the distance of their centres of gravity from the neutral axis.

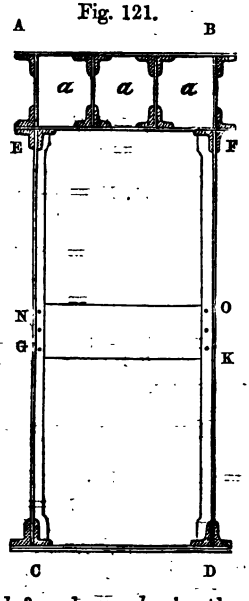
Digitized by Google

Special investigations of this theorem are given in Art. 62 and 63, showing the magnitude of the parts neglected.

66. *To determine the strength, &c., of a Tubular Beam.*—A B C D, composed of a series of cells, A F, with angle-iron, at the top part, and of thick solid plates, C D, at the bottom part, the cells being formed as described in fig. 121.

Here the section of the beam may be divided into three portions, viz., the cells at the top, the bottom plates, and the side plates.

Fig. 121.




For the position of the neutral axis N O we have by eq. (1), Art. 64,

$$h = \frac{1}{K}(a_0 \alpha_0 + a_1 \alpha_1 + a_2 \alpha_2) \quad \ldots \quad (I)$$

where $a_0$, $a_1$, $a_2$ are the areas of the material in the side plates, in the top cells, and in the bottom plates, respectively; and so on.

If D = A C, the depth of the beam, then $h_1 = D - h$.

From eq. (2), Art. 64, we get

$$I_0 = Q_0 + Q_1 + Q_2 + a_0 (h - \alpha_0)^2 + a_1 (h - \alpha_1)^2 + a_2 (h - \alpha_2)^2 \quad \ldots \quad (2)$$

where $Q_1$, the moment of inertia of the top cells, about their centre of gravity, is given in eq. (9), Art. 35.

$Q_2$ = the moment inertia bottom plate C D about its centre of gravity = $\frac{1}{12} a^2 k_2^2$, where $k_2$ is the thickness of the plate.

$Q_0$ = the moment inertia of the side plates about their centre of gravity = $\frac{1}{12} a_0 d_0^2$.

Where $d_0$ = the length of the plates, with the relation, $\alpha_0 = d + \frac{d_0}{2}$, the depth of the cells A E being $d$.

If the beams be loaded in the middle and supported at the ends, then $M = \frac{1}{4} W l$, and

$$\frac{1}{4} W l = M = \frac{S}{h} I_0 \text{ or } \frac{S_1}{h_1} I_0,$$

$$\therefore W = \frac{4 S I_0}{h l} \text{ or } \frac{4 S_1 I_0}{h_1 l} \quad \ldots \quad (3)$$

Digitized by Google

which gives the load corresponding to any assumed value of S or $S_1$. Conversely S or $S_1$ may be determined for any given load, W.

1. The following is a more simple and practical method of calculating (approximately) the strength of these beams:

Putting $a$, $a_1$ for the areas of the top and bottom parts respectively; $g$, $g_1$ for the distance of their respective centres of gravity from N O; and $G = g + g_1$; neglecting the side plates,—for the position of the neutral axis, we have

$$a\,g = a_1\,g_1 \quad \ldots \quad (4)$$

And from *General Theorem* II., Art. 65, we get

$$I_0 = a\,g^2 + a_1\,g_1^2 = a\,g\,(g + g_1) \text{ or } a_1\,g_1\,(g+g_1)$$
$$= a\,g\,G \text{ or } a_1\,g_1\,G \quad \ldots \quad (5)$$
$$\therefore M = \frac{S}{h}\,a\,g\,G \text{ or } \frac{S_1}{h_1}\,a_1\,g_1\,G$$
$$= S\,a\,D \times \frac{g\,G}{h\,D} \text{ or } S_1\,a_1\,D \times \frac{g_1\,G}{h_1\,D}$$
$$= S\,a\,D \text{ or } S_1\,a_1\,D, \text{ nearly} \quad \ldots \quad (6)$$

taking $\frac{g\,G}{h\,D}$ and $\frac{g_1\,G}{h_1\,D}$ as constants, each being nearly equal to unity.

If K be put for the whole section, and taking $\frac{S\,g\,G}{h\,D} = \frac{S_1\,g_1\,G}{h_1\,D}$ = a constant, we get

$$M = C\,(a + a_1)\,D = C\,K\,D \quad \ldots \quad (7)$$

Here *the strength varies as the product of the top or bottom areas multiplied by the depth.*

When $M = \frac{1}{4}\,W\,l$ we get

$$W = \frac{4\,S\,a\,D}{l} \text{ or } \frac{4\,S_1\,a_1\,D}{l} \quad \ldots \quad (8)$$

A similar formula may be derived for beams with double flanges, as described in fig. 119.

From the experiments on the model Conway tube, we find $S_1 = 16{\cdot}5$ tons; hence we have

$$W = \frac{66\,a_1\,D}{l} \quad \ldots \quad (9)$$

which is the formula usually employed for calculating the strength of these beams. Where W is expressed in tons, $a_1$ being the area of the bottom plate in inches, D the whole depth of the beam, and $l$ the distance between the two supports expressed in the same units as D.

Digitized by Google

In cast-iron beams with double flanges, as derived from the experiments of the late Mr. Hodgkinson,

$$w = \frac{26\, a_1\, D}{l} \quad \ldots (10)$$

67. *Maximum strength with a given section of material.*

When the material in the transverse section of a hollow beam, or of a beam with double flanges, is properly distributed, the material at the top should be yielding to the force of compression whilst the material at the bottom is yielding to the force of extension.

When the side plates of a tubular beam (or the central rib of a double-flanged beam) are neglected eq. (6), Art. 66, gives us the relation

$$s\, a = s_1\, a_1, \text{ or } \frac{a}{a_1} = \frac{s_1}{s} \quad \ldots (1)$$

that is, *the areas should be* (approximately) *in the inverse ratio of the resistance of the material.*

The results of experiment closely confirm the truth of this deduction. In wrought-iron girders for example, the bottom section is about $\frac{5}{6}$ of the top section; and in cast-iron beams the section of the bottom flange is about $6\frac{1}{2}$ times that of the top flange, which is approximately, in the case of cast iron, the ratio of the resistance of compression to that of extension.

In general, eq. (2) and (3), Art. 12, give the strict conditions on which the maximum strength should be calculated.

To determine the thickness, $x$, of the bottom plate, CD, fig. 121, corresponding to this condition; let $k$ = the thickness of the side plates; $b$ = AB; $d$ = AE; and so on, as in the foregoing article; then taking NO as the axis of moments, by Art. 8, we get

$$a\left(h - \frac{d}{2}\right) + k\,(h-d)\frac{h-d}{2} = b\,h_1 \times \frac{h_1}{2} - (b-k)(h_1-x)\frac{(h_1-x)}{2}$$

$$\therefore x = h_1 - \sqrt{\frac{b\,h_1^2 - a\,(2\,h-d) - k\,(h-d)^2}{b-k}}$$

where $h$ and $h_1$ are given in eq. (2) and (3), Art. 12.

## *Strength of an Iron Ship.*

68. To determine the strength, &c. of an iron ship, the

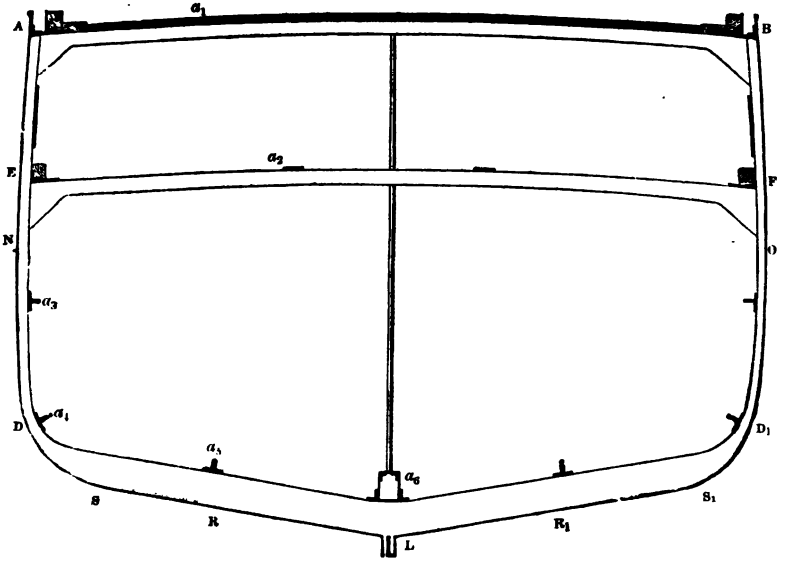


Digitized by Google

transverse section being represented in the annexed diagram; A B and E F the upper and lower decks; A D and B $D_1$ the sides down to the bilge; L R, R S, S D, &c., a series of plates, assumed to be straight, forming the bottom, and so on.

Having divided the section into a convenient number of parts, formulæ (1) and (2), Art. 64, give the most exact method of calculating the moment of inertia of the whole section; where the moment of inertia of each part about its centre of gravity must be determined, and so on. The foregoing investigations give the moments of inertia of all the forms that may be required in this calculation. But the following method of calculation is more simple and sufficiently exact for all practical purposes.

Fig. 122.




Put $a_1$ for the area of the material in the upper deck; $a_2$ for that of the lower deck; $a_3$ for the lower hold stringers; $a_4$ for the bilge keelsons; $a_5$ for the sister keelsons; $a_6$ for the middle keelson; $a_7$ for the keel-piece L; $a_8$ for the plates L R L $R_1$; $a_9$ for the plates R S $R_1$ $S_1$; $a_{10}$ for the plates S D $S_1$ $D_1$; $a_0$ for the side plates A D B $D_1$ down to the top of bilge, $d_0$ being their depth;

Digitized by Google

and so on as before; then eq. (1) and (3), Art. 64, 65, will become

$$h = \frac{1}{K} \Sigma_0^{10} a_n \alpha_n \ \ldots \ (1)$$

$$I_0 = Q_0 + \Sigma_0^{10} a_n (h - \alpha_n)^2 = \frac{1}{12} a_0 d_0^2 + \Sigma_0^{10} a_n (h - \alpha_n)^2 \ \ldots \ (2)$$

where $Q_0$ is the moment of inertia of the side plates about their centre of gravity. It will be observed that $(h - \alpha_n^2)$ is always positive.

And we further have

$$M = \frac{S}{h} I_0 \text{ or } \frac{S_1}{h} I_0 \ \ldots \ (3)$$

and

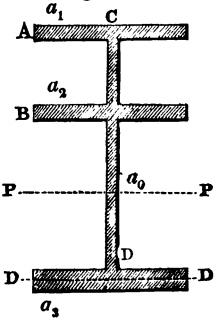
$$S = \frac{M h}{I_0}, \ S_1 = \frac{M h_1}{I_0} \ \ldots \ (4)$$

If the plates A E and E D have not the same thickness, then $Q_1$ of formula (3), Art. 65, must be retained, and $Q_0$ and $Q_1$, calculated accordingly.

If the ship be supported at its extremities, and the load distributed as described in Art. 23, then eq. (6) or (2), according to circumstances, will give the value of M in the foregoing formulæ; or if the ship be supported at the centre, then eq. (10) or (11), Art. 25, will give the value of M, and so on to other cases.

69. To adopt a more summary, though less accurate method of calculation, let A D represent the section of the material of an iron ship; the flange $a_1$ the section of the materials of the main deck; the flange $a_2$ the section of the lower deck; the flange $a_3$ the section of the bottom; $a_0$ the section of the material in the side plates or rib, $d_0$ being the depth, and so on as before. In this case eq. (1) and (2), Art. 68, become

Fig. 123.




$$h = \frac{1}{K} (a_0 \alpha_0 + a_1 \alpha_1 + a_2 \alpha_2 + a_3 \alpha_3) \ \ldots \ (5)$$

$$I_0 = \frac{1}{12} a_0 d_0^2 + a_0 (h - \alpha_0)^2 + a_1 (h - \alpha_1)^2 + a_2 (h - \alpha_2)^2 + a_3 (h - \alpha_3)^2 \ \ldots \ (6)$$



Digitized by Google

If we take $d_0 = D$ the whole depth of the section, $a_2 = D$, $a_0 = \frac{1}{2} D$, and $a_1 = 0$, these formulæ become

$$h = \frac{1}{K} \{(\tfrac{1}{2} a_0 + a_3) D + a_2 \alpha_2\} \ldots (7)$$

$$I_0 = a_0 \left\{\frac{1}{12} D^2 + (h - \tfrac{1}{2} D)^2\right\} + a_1 h^2 + a_2 (h - \alpha_2)^2 + a_3 (h - D)^2 \ldots (8)$$

70. To determine the area, $a_1$, of the material in the transverse section of the upper deck (fig. 123) so as to have a maximum strength with a given amount of material.

The strains on a ship afloat are somewhat different from the strains on an ordinary fixed girder; for it is found that the upper part of the transverse section of a ship when afloat is sometimes subjected to compression and at other times to that of extension. But of these two strains the former is generally the more violent. It will therefore be expedient, in calculating the distribution of the material in the section of an iron ship, to regard the upper portion of the section as that which is subjected to extension; and therefore, in this case, we should have $h = \frac{D}{r+1}$. See Art. 12 and 67.

Making this substitution in eq. (7), Art. 69, and putting $a_0 + a_1 + a_2 + a_3$ for K, we get

$$a_1 = \frac{r+1}{D} \{(\tfrac{1}{2} a_0 + a_3) D + a_2 \alpha_2\} - (a_0 + a_2 + a_3) \ldots (1)$$

If we assume $r = 1$, then this expression becomes

$$a_1 = a_3 - a_2 + \frac{2 a_2 \alpha_2}{D} \ldots (2)$$

1. In one of our most approved iron ships, $a_0 = 440$ sq. in., $a_2 = 156$, $a_3 = 490$, $D = 23\frac{1}{2}$ ft., $\alpha_2 = 7\frac{1}{2}$ ft.; required $a_1$.

Substituting these values in eq. (1), we find $a_1$, or the area of the upper deck, to exceed 300 square inches. Now in this iron ship the equivalent area of the upper deck is only about 230 square inches; hence it appears that this portion of the ship should be about one-half stronger than it is, in order to have a proper distribution of the material.

71. When the ship is constructed of a combination of wood and iron, it is necessary to observe that the section of the timber should only be taken into calculation when it has to resist the

Digitized by Google

force of compression, and that, in this case, the resistance of the timber may be taken upon an average at about $\frac{1}{7}$ of that of wrought iron, or what amounts to the same thing, about $\frac{1}{7}$ of the sectional area of the timber may be taken as the equivalent area of iron.

## STRENGTHS OF SIMILAR BEAMS.

72. *The neutral axis in similar beams divides the vertical axis proportionally.*

Let $r$ = the linear ratio of the parts of two beams in all respects similar in section. An accent being used to symbolise similarity.

By eq. (1), Art. 64,

$$h = \frac{1}{K} \Sigma_0^n a_n \alpha_n$$

Now $K' = r^2 K$, $a'_n = r^3 a_n$, $\alpha'_n = r\alpha_n$, and so on,

$$\therefore h' = \frac{1}{K'} \Sigma_0^n a'_n \alpha'_n = \frac{1}{r^2 K} \Sigma_0^n r^3 a_n \alpha_n = \frac{r}{K} \Sigma_0^n a_n \alpha = r h \ldots (1)$$

Similarly $h'_1 = r h_1$, and $\therefore \frac{h'}{h'_1} = \frac{h}{h_1}$, which is the analytical expression of the theorem.

73. *The moments of inertia of two similar surfaces about their neutral axes are to each other as the fourth powers of their linear dimensions.*

By eq. (3) Art. 10, $I = \frac{1}{3} \Sigma b (q^3 - e^3)$, and

$I' = \frac{1}{3} \Sigma b' (q'^3 - e'^3) = \frac{1}{3} \Sigma r b (r^3 q^3 - r^3 e^3) = \frac{1}{3} r^4 \Sigma b (q^3 - e^3)$

$= r^4 I$

Similarly $I'_1 = r^4 I_1$;

$$\therefore I'_0 = I' + I'_1 = r^4 (I + I_1) = r^4 I_0 \ldots (2)$$

which is the analytical expression of the theorem.

74. *The moments of rupture of similar surfaces are to each other as the cubes of their linear dimensions.*

Here we have, $M = \frac{S}{h} \cdot I_0$, and

$$M' = \frac{S}{h'} \cdot I'_0 = \frac{S}{r h} r^4 I_0 = r^3 \frac{S}{h} I_0 = r^3 M \ldots (3)$$

Digitized by Google

When $b$, the breadth of the beams, is constant, the other parts being similar,

$$\mathrm{I}' = \tfrac{1}{3}\, b\, \Sigma\,(q'^3 - e'^3) = r^3\, \mathrm{I}$$
$$\therefore\ \mathrm{I}'_0 = \mathrm{I}' + \mathrm{I}'_1 = r^3\,(\mathrm{I} + \mathrm{I}_1) = r^3\, \mathrm{I}_0$$
$$\therefore\ \mathrm{M}' = \frac{\mathrm{S}}{h'}\mathrm{I}_0 = \frac{\mathrm{S}}{r\,h}\, r^3\, \mathrm{I}_0 = r^2\, \mathrm{M} \quad \ldots\ (4)$$

In this case, the *strength varies as the square of the linear dimensions.*

75. *The breaking weights of similar beams are to each other as the squares of their linear dimensions, or as their sectional areas.*

Here we have, $\mathrm{W} = \dfrac{n\,\mathrm{M}}{l}$, and

$$\mathrm{W}' = \frac{n\,\mathrm{M}'}{l'} = \frac{n \times r^3\,\mathrm{M}}{r\,l} = r^2 \times \frac{n\,\mathrm{M}}{l} = r^2\,\mathrm{W} \quad \ldots\ (5)$$

$$\text{but } r^2 = \frac{\mathrm{K}'}{\mathrm{K}}\ ;\ \therefore\ \frac{\mathrm{W}'}{\mathrm{W}} = \frac{\mathrm{K}'}{\mathrm{K}}$$

76. A model beam, whose length is $l$ inches, and moment of rupture $\mathrm{M}$, is capable of supporting a weight $\mathrm{W}$ applied at its centre, the extremities being supported; another beam, having a *similar* section, is to be $l_1$ inches long, and to support the weight $\mathrm{W}_1$ applied at its centre; required the linear ratio $r$ of the similar sections.

$$\text{Here } \mathrm{M} = \frac{\mathrm{W}\,l}{4},\ \text{and } \mathrm{M}' = \frac{\mathrm{W}_1 l_1}{4};\ \text{but } \mathrm{M}' = r^3\,\mathrm{M} = \frac{r^3\,\mathrm{W}\,l}{4};$$

$$\therefore\ r^3\,\mathrm{W}\,l = \mathrm{W}_1\, l_1\ ;\ \therefore\ r = \sqrt[3]{\frac{\mathrm{W}_1\, l_1}{\mathrm{W}\,l}} \quad \ldots\ (6)$$

$$\text{And if } l_1 \text{ be required, } l_1 = \frac{r^3\,\mathrm{W}\,l}{\mathrm{W}_1} \quad \ldots\ (7)$$

In the model Conway beam, $l = 900$ inches, $\mathrm{W} = 90$ tons; then for a beam having a similar section, we get

$$r = \sqrt[3]{\frac{\mathrm{W}_1\, l_1}{81000}},\ \text{where } \mathrm{W}_1 \text{ is in tons and } l_1 \text{ in inches.}$$

If $\mathrm{W}$ and $\mathrm{W}_1$ be the displacements of two ships of similar transverse sections; then $\dfrac{\mathrm{W}_1}{\mathrm{W}} = \dfrac{r^2\, l_1}{l}$, therefore by substitution in eq. (6), we get

$$r = \frac{l_1^2}{l^2} \quad \ldots\ (8)$$

Digitized by Google

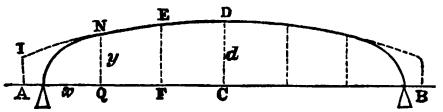
Here $l$ being the length of a model ship, $l_1$ the length of another ship, which is to have its section similar to that of the former, then this formula gives the linear ratio of the parts of this similar section, so that the two ships may have equal strengths.

## BEAMS OF GREATEST ABSOLUTE STRENGTH.

77. In Arts. 12 and 67 the distribution of the material in the section of a beam has been determined so as to give the greatest strength. Now we propose to determine the law of variation of the transverse sections of a beam, so that the strength may be a maximum, the amount of material being given. This condition will be fulfilled when the beam is upon the point of rupture at all sections at the same time; that is, when the moment of rupture $M_1$ for any section is equal to the moment of the pressure, acting on the beam, tending to produce rupture at that section.

78. A beam A B is supported at its extremities, and the load W is *uniformly distributed throughout its length.* To find the form of greatest strength.

Fig. 124.




Let $a = A C = C B$; $d = C D$; M, $M_1$ = the moments of rupture of sections C D, Q N respectively; $x = A Q$, $y = Q N$.

By dividing eq. (6) by eq. (7), Art. 16, we get

$$\frac{M_1}{M} = \frac{4 A Q \times Q B}{AB^2} = \frac{1}{a^2} x (2a - x) \quad . \quad . \quad . \quad (1),$$

where we have to determine M and $M_1$ for the given form of the section of the beam.

*Case* 1. When all the transverse sections are *rectangular* having the same breadth, $b$.

Digitized by Google

$M_1 = \frac{1}{6} S b y^2$ and $M = \frac{1}{6} S b d^2$, therefore by eq. (1)

$$y^2 = \frac{d^2}{a^2} x (2a - x) \quad . \quad . \quad . \quad (2),$$

The equation to an ellipse, whose major diameter is A B, and centre C.

Here the dimension of the section at C D is determined by the equation $W = \frac{2 S b d^2}{3 a}$.

*Case* 2. Where the beam is *any kind of girder*, whose sections are similar.

By eq. (3), Art. 74, $\frac{M_1}{M} = r^3 = \frac{y^3}{d^3}$; therefore by eq. (1) we get

$$y^3 = \frac{d^3}{a^2} x (2a - x) \quad . \quad . \quad . \quad (3),$$

which is the equation of the curve A N D.

To construct beams exactly of these geometrical forms is obviously impracticable; we may, however, give these results a practical application as follows:

Let A G, fig. 124, be divided into three equal parts in the points F and Q; then E F and N Q will be the depths of the beam at these parts, and N I, a tangent to the point N of the curve, may be extended so as to give a sufficient hold upon the support at A.

Again, let $M = s k d$ be the moment of rupture of a tubular girder, of *constant breadth*, at the centre C, where $k$ = bottom area of the section at C D, and $d$ = C D; these symbols being accented for the corresponding parts of the sections F E and Q N; moreover, let $t$ = thickness of plates forming the section between C D and F E; $r t$ = their thickness between F E and Q N; $r^2 t$ = their thickness between Q N and A I; then,

substituting $\frac{2}{3} a$ for $x$ in eq. (1) we get $\frac{M_1}{M} = \frac{8}{9}$, but

$$\frac{M_1}{M} = \frac{s k_1 d_1}{s k d} = \frac{r k d_1}{k d} = \frac{r d_1}{d}; \therefore \frac{r d_1}{d} = \frac{8}{9}; \text{ and}$$

$\therefore d_1 = \frac{8d}{9r}$, which gives the depth of the beam at the section E F.

Digitized by Google

Similarly, by substituting $\frac{1}{3}a$ for $x$ in eq. (1), for the section at Q N, we get—

$$\frac{M_2}{M} = \frac{5}{9}, \text{ also } \frac{M_2}{M} = \frac{r^3 d_2}{d}, \text{ and } \therefore\ d_2 = \frac{5d}{9r^2}, \text{ which}$$

gives the depth of the beam at the section Q N.

79. When the weight W is applied *to the middle of the beam* A B. See fig. 124.

Dividing eq. (5) by eq. (3), Art. 15, we get

$$\frac{M_1}{M} = \frac{AQ}{AC} = \frac{x}{a} \quad . \quad . \quad . \quad (1),$$

where M and $M_1$ must be determined from the given form of the section of the beam.

Taking *Case* 1, for example, by substituting these values of $M_1$ and M in eq. (1) above given, we get

$$y^2 = \frac{d^2}{a} x \quad . \quad . \quad . \quad (2),$$

which is the equation of a parabola, whose vertex is at A, and axis A C, the curve D B being identical with the curve A D.

Taking *Case* 2, similarly by substitution in eq. (1), we get

$$y^3 = \frac{d^3}{a} x \quad . \quad . \quad . \quad (3),$$

which is the equation of a cubical parabola.

80. A beam A B (fig. 102) is *fixed at one extremity*, and loaded with a weight W at the other extremity. To find the form of greatest strength.

Dividing eq. (8) by eq. (9), Art. 17, we get

$$\frac{M_1}{M} = \frac{AQ}{AB} = \frac{x}{2a} \quad . \quad . \quad . \quad (1).$$

Taking *Case* 1, by substitution in this equality, we get

$$y^2 = \frac{d^2}{2a} x \quad . \quad . \quad . \quad (2).$$

Taking *Case* 2, we get

$$y^3 = \frac{d^3}{2a} x \quad . \quad . \quad . \quad (3).$$

81. When the weight W is *uniformly distributed throughout the length of the beam.* See fig. 102.

Digitized by Google

Dividing eq. (11) by eq. (12), Art. 18, we get

$$\frac{M_1}{M} = \frac{A\,Q^2}{A\,B^2} = \frac{x^2}{4\,a^2} \quad . \quad . \quad . \quad (1).$$

Taking *Case* 1, we get

$$y^2 = \frac{d^2}{4\,a^2}\,x^2, \quad \therefore\ y = \frac{d}{2\,a}\,x \quad . \quad . \quad . \quad (2)$$

which is the equation of a straight line joining the lower edge at A, and the upper edge at B.

Taking *Case* 2, we get

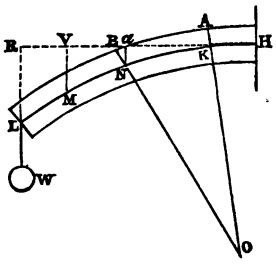
$$y^2 = \frac{d^2}{4\,a^2}\,x^2 \quad . \quad . \quad . \quad (3)$$

## DEFLECTION OF BEAMS.

82. A beam L B A H, fixed at one extremity, is bent by a weight W suspended from the other extremity L. To find the curve of deflection, &c.

Let $c$ = N K = A $a$, the length of a small portion of the neutral axis L N K H; $R$ = O K = O N, the radius of curvature of the neutral line N K; $h$ = K A = N $a$, the distance of the upper side of the beam from the neutral axis; $c_1$ = B $a$, the extension of the fibre A $a$ by the force $s\,h$; E, the modulus of elasticity; and so on.

Fig. 125.




The force to produce the elongation $c_1 = \frac{E\,c_1}{c}$;

$$\therefore\ s\,h = \frac{E\,c_1}{c};\ \therefore\ s = \frac{E\,c_1}{h\,c};$$

But by the similar triangles, O N K and N B $a$, $\frac{c_1}{c} = \frac{h}{R}$;

$$\therefore\ s = \frac{E}{R};$$

$$\therefore\ M = s\,I_0 = \frac{E}{R}\,.\,I_0 \quad . \quad . \quad . \quad (1).$$

Now let H N M L be the curve of deflection of the neutral axis, and taking H as the origin of rectangular co-ordinates, let

Digitized by Google

$x = \text{H V}$, $y = \text{M V}$, $a = \text{H R}$, the length of the beam, and $\delta = \text{R L}$, the greatest deflection.

By eq. (10), Art. 17, $\text{M} = \text{W} \times \text{R V} = \text{W}(a - x)$; therefore we get

$$\frac{1}{\text{R}} = \frac{\text{W}}{\text{E I}_0}(a - x) \quad . \quad . \quad . \quad (2).$$

The expression for the radius of curvature R is given in mathematical works. (See Tate's 'Calculus,' p. 215). Now $\frac{dy}{dx}$ of this expression is equal to the tangent of the angle which a line touching the curve at M makes with H R; but for small deflections the tangent of this angle is small as compared with unity, and consequently $\left(\frac{dy}{dx}\right)^2$ may be neglected in the expression for R; hence we find $\frac{1}{\text{R}} = \frac{d^2y}{dx^2}$; therefore, by eq. (2),

$$\frac{d^2y}{dx^2} = \frac{\text{W}}{\text{E I}_0}(a - x),$$

Successively integrating between the limits $x$ and $o$, we get

$$y = \frac{\text{W}}{\text{E I}_0}\left(\frac{ax^2}{2} - \frac{x^3}{6}\right) \quad . \quad . \quad . \quad (3)$$

which is the equation of the curve of deflection.

When $y = \text{R L} = \delta$, $x = a$; then eq. (3) becomes—

$$\delta = \frac{\text{W}\,a^3}{3\,\text{E I}_0} \quad \ldots \quad (4),$$

which is the *greatest deflection of a beam loaded at one extremity and fixed at the other.*

83. When a beam is *supported at its extremities and loaded in the middle* with the weight W, $a$ being the distance between the supports (see fig. 3); then the deflection at C is produced by a force $\frac{\text{W}}{2}$ applied at the distance $\frac{a}{2}$ from the point C. In this case, therefore, the greatest deflection will be found by substituting $\frac{\text{W}}{2}$ for W, and $\frac{a}{2}$ for $a$, in eq. (4)

$$\therefore \quad \delta = \frac{\text{W}\,a^3}{48\,\text{E I}_0} \quad \ldots \quad (5)$$

Digitized by Google

When the beam is rectangular $I_0 = \frac{1}{12} bd^3$, and

$$\therefore \delta = \frac{W a^3}{4 E b d^3} \quad \ldots (6)$$

If the beam be upon the point of rupture, $W a = \frac{2}{3} S b d^2$, and

$$\therefore \delta = \frac{S a^2}{6 E d} \quad \ldots (7)$$

which expresses *the ultimate deflection of the beam.*

84. The *ultimate deflections of similar beams are to each other as their linear dimensions.*

By Arts. 73 and 85, $I_0' = r^4 I_0$, and $W' = r^2 W$,

$$\therefore \frac{\delta'}{\delta} = \frac{W' a'^3}{48 E I_0'} \div \frac{W a^3}{48 E I_0} = r \ldots (8)$$

When the beams are similar in section but varying in length.

By eq. (2) Art. 76, $I_0' = r^4 I_0$, $W_1 a_1 = r^3 W a$, therefore, by eq. (6) we get—

$$\frac{\delta'}{\delta} = \frac{1}{r} \frac{a_1^2}{a^2} \quad \ldots (9)$$

85. A beam is supported at its extremities, and a force is applied at its centre. To find the *work*, U, expended in the deflection of the beam.

Here making $\delta$ and w variable and $I_0$ constant in eq. (5) we get, by differentiation, &c.,

$$d U = W d \delta = \frac{a^3}{48 E I_0} W d W;$$

$$\therefore U = \frac{a^3}{48 E I_0} \int_0^W W d W = \frac{a^3 W^2}{96 E I_0} \quad \ldots (10)$$

By substituting the value of the deflection, eq. (5), this equality becomes

$$U = \tfrac{1}{2} W \delta \quad . \quad . \quad . \quad (11)$$

that is, *the work is equal to one-half the pressure multiplied by the corresponding deflection.*

Now when the beam is rectangular and rupture is about to take place, $I_0 = \frac{1}{12} b d^3$, &c. then eq. (10) becomes

$$U = \frac{S^2}{18 E} a b d = \frac{S^2}{18 E} a K \quad . \quad . \quad . \quad (12)$$

which is the *work* expended in producing rupture, where it will be observed that *the work varies as the sectional area multiplied by the length, or as the solid content of the beam.*

Digitized by Google

Comparing this equality with eq. (7), Art. 4. we get

$$U_1 = 9\,U \quad . \quad . \quad . \quad (13)$$

that is, *the work expended in producing fracture in a bar by elongation is nine times the work expended in producing transverse fracture when the bar is supported at its extremities and loaded in the middle.*

Adopting the notation of Art. 4, from eq. (12), we get

$$U = u\,K\,L \quad . \quad . \quad . \quad (14)$$

Where $u$, *the modulus of dynamic resistances,* being constant for the same kind of material, *gives us a comparative measure of the resistance of different kinds of material to a force of impact tending to produce transverse rupture.*

Digitized by Google

Digitized by Google

# APPENDICES.

Digitized by Google

Digitized by Google

# APPENDIX I.

## REPORT OF THE COMPARATIVE PROOFS OF FIVE EXPERIMENTAL 24-POUNDER GUNS.

Six experimental 24-pounder guns—cast under the direction of Mr. Fairbairn by the Bank Quay Foundry, Warrington, during the months of August and September 1855—were made for the purpose of ascertaining by experiment in how far it was possible to improve the quality of the iron, and under what conditions cast-iron ordnance should be treated in the operation of moulding, cooling, &c. The castings were lettered A, B, C, D, E, and F. Letter F was cast with a core, but the great heat caused it to adhere to the metal, and the cast was in consequence a failure. The other five were gauged, examined, and proved in the Arsenal on the 9th and 23rd October 1855. Subsequently they were removed to the marshes, and the experiments for testing their comparative merits commenced on the 30th November and ended on the 21st December of the same year.

After three days' firing letter C gun burst. It was then deemed expedient to substitute cylinders of equal gross weight to the large number of shot and wads which had been used up to that time. In consequence of this arrangement an interval of ten days elapsed, during which the cylinders were prepared.

The guns were placed on the ground, their muzzles being supported by blocks of wood, as used in the proof of ordnance. Sods of earth were placed behind them for the first few rounds, but they diminished the recoil to such a trifling extent that large beams of wood were substituted. Even these proved insufficient to resist the recoil when the guns were heavily shotted. One beam 12 inches square was split through its entire length, 13 feet, by a single discharge, the force of the discharge having been against the breech or the button end of the gun.

As the guns continued to recoil up the slope, holes were dug in the stiff clay about 2 feet deep to receive them; this reduced the recoil from 10 or 12 feet to as many inches. Still they steadily worked their way even into the clay, in consequence of which new holes were dug,



Digitized by Google

and heavy piles of timber driven into the ground with cross-beams to receive the first shock. By this means the labour of loading was much diminished, and the bulkheads effectually resisted any further recoil. The guns too, being sunk below the surface of the ground, were prevented from injuring the adjacent ones when they burst.

The proof was carried on with portfire and clay in the usual manner:—

| | lbs. | p. shot | wads | |
|---|---|---|---|---|
| 1st series | 8 | 2 | 2 | All stood 5 rounds. |
| 2nd „ | 8 | 3 | 2 | „ |
| 3rd „ | 10 | 3 | 3 | „ |
| 4th „ | 10 | 4 | 4 | C burst at second round; all the others stood 5 rounds. |
| 5th „ | 12 | 4 | 4 | All stood 5 rounds. |
| 6th „ | 12 | 5 | 5 | „ |

Cylinders averaging 144 lbs., or equal to six spherical shot, were here substituted for that number, and one wad over the powder was henceforth only used:—

| | lbs. | p. shot | wad | |
|---|---|---|---|---|
| 7th series | 12 | 6 | 1 | All stood 2 rounds. |
| 8th „ | 14 | 7 | 1 | D burst 2nd round.<br>B „ 3rd „<br>A, E „ 4th „ |

D having burst at the second round, it was considered better to give the remaining ones another round with the same charges of powder and weight of shot, instead of increasing them as usual after two rounds. The result proved this had been judiciously proposed, as B burst after the 3rd, and A and E together at the 4th round.

From the foregoing it follows that—

| | | |
|---|---|---|
| C | burst at the | 17th round. |
| D | „ | 31st „ |
| B | „ | 32nd „ |
| A and E | „ | 33rd „ |

It was not possible to recover the whole of the fragments, but in each case the greater number have been found, and, as far as can be ascertained from these data—

| | | |
|---|---|---|
| A | burst into | 15 pieces. |
| B | „ | 24 „ |
| C | „ | 19 „ |
| D | „ | 17 „ |
| E | „ | 16 „ |

the small fragments not included.

Digitized by Google

Distance of the fractures from the muzzle :—

| | | | |
|---|---|---|---|
| In A | 4 feet | 6 inches. | Right trunnion left on. |
| B | 3 „ | 6 „ | Lost both trunnions. |
| C | 4 „ | 5 „ | Left trunnion left on. |
| D | 4 „ | 6 „ | Left trunnion left on. |
| E | 4 „ | 7 „ | Lost both trunnions. |

The muzzles of the guns in each case (except E, which was not observed) were found pointing to the left after bursting.

From the position in which each stood at the time of bursting, the breeches were prevented from flying off far to the rear. Those of B, C, and D buried themselves in the bank; that of A, and also of E, fell into the ditch a few yards in rear. In these two guns the first fracture evidently took place in the lower half of the gun, for the holes made in the earth were deeper and wider than the rest, some fragments of E being buried 3 feet in the earth. The cascable of each of the guns was blown upwards clear of the bulkheads in rear, and fell into the ditch in one case, and on the bank in the other. The fragments of these guns also were carried to a greater distance by the explosion than those of the others, some falling into the river on the left, and others going several hundred yards to the right—one as much as 700 yards. This proves the resistance offered by these guns to the bursting force of the powder to have been very great.

The directions in which the principal fragments of each gun flew were very similar. It was observed that in almost every case two pieces from about the first reinforce fell into the field on the further side of the manor ward.

A fragment from the second reinforce of D, which must have risen to a considerable height, struck the top of the traverse beneath which the party had taken shelter, and fell close to them.

Another from the same part of B, and of a similar size and shape, fell within three yards of the same spot.

The trunnions of B, with but little metal attached, were found nearly touching each other in their original position, the body of the gun having been blown from between them.

The cylinder and shot where each gun burst were driven out by the explosion as usual, except in the case of A, where one-half the cylinder was found among the pieces of the gun, and near the spot on which it had stood. The gun had evidently burst before the *vis inertia* of the charge had been overcome, and the escaping gas forcing the sides of the cylinder against the fracture broke it in two—one part going into the butt, the other remaining with the fragments of the gun. The fracture of the muzzle portion of this gun bears marks of having acted



Digitized by Google

as a fulcrum. The fractured surfaces of C and D guns and the general direction of the lines of separation indicate great similarity in the structure of the metal. It will be observed that they broke at the same distance from the muzzle, the left trunnion remained on each, and they broke into 19 and 17 pieces. B burst nearer the muzzle than any other, and into the greatest number of pieces. The fractured surfaces were regular and even, with the exception of the cascable which was much torn.

The surfaces of A are irregular and ruffled except the cascable, which is very smooth. This gun and also E burst in the line of the vent, and the end of the bore in each of the five guns was left perfect.

The appearance presented by the fragments of E was indicative of a greater degree of tenacity than any of the others. The cascable especially was torn in a singularly irregular manner.

Judging from the appearance of the fragments, the order in which the guns would stand are E (best), then A, C, D, and B.

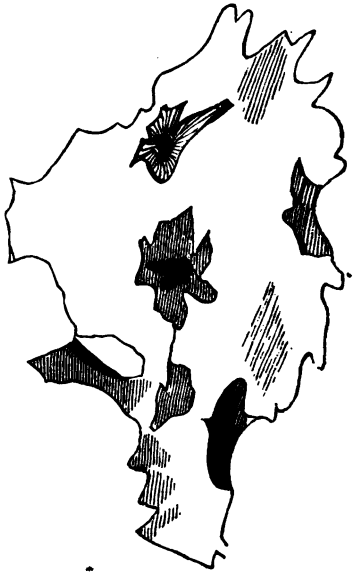
| | | | | | | |
|---|---|---|---|---|---|---|
| One | fragment | of C | 2½ | cwt. fell | 250 | yards to the right. |
| One | „ | D | 2½ | „ | 300 | „ left. |
| Two | „ | B | 4 | „ | 300 | „ „ |
| One | „ | A | 5 | „ | 450 | „ „ |
| One | „ | E | not recovered | | 700 | „ right. |

Minute portions of each gun were also examined under the microscope, and gave results as follows:—

(A) This specimen did not exhibit a crystalline structure, its surface was much indented with a few pointed projections—bright silvery globules in considerable numbers.

(A)

(B)

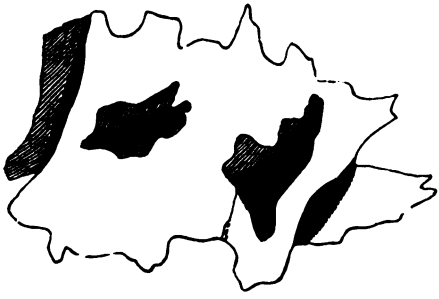


(B) Specimen larger than A, moderately-sized crystals apparently cubical. Surface less rugged than A, and inferior to it in general indications of tenacity.

Digitized by Google

(D) Crystals larger than either of the preceding, one long and deep chasm. Surface of crystals bright, inferior to A and B.

(D)



(C) Difficulty experienced in breaking off this specimen, the metal being harder than the rest. Large crystals with laminated surfaces—not all bright—sound—blunt projections, no fine points.

(C)

(E)

Digitized by Google

(E) This specimen, larger than any of the preceding, exhibited under the microscope a beautiful appearance, resembling H to some extent. No well-defined crystals visible, but a rugged deeply-indented surface with bright globules very minute, and many sharp projecting points, apparently superior in adhesive properties to any of the others.

The order in which the microscopical appearance would cause the guns to stand is—E, A, B, D, C.

The temperature was not observed when C was burst; it was probably about 40° Fahrenheit. D went at 32°—A and E at 20°.

As iron is a peculiarly sensitive metal, and becomes brittle during frost, the fact that E and A stood five rounds each with six shot, and upwards when the thermometer stood below the freezing-point, speaks highly in favour of these guns. And it should not be omitted that they were at the time of bursting partly imbedded in the ground, which, by preventing the frost from equally affecting every part, must have tended to weaken them. A gun being able to withstand the bursting force of the powder for even a single round more than another, under such circumstances as these, indicates considerable superiority in the tenacity of the metal.

It appears then from the foregoing that E and A stood the greatest number of rounds, and were burst under more disadvantageous circumstances than C or D, that they burst in the fewest number of fragments, and that the muzzle portion is of greater length in these than in the others: also that the pieces of the guns flew to the greatest distance, and that the general appearance of the fractured surfaces is in favour of these guns. They must therefore be considered as much better guns than the rest. In determining between these two we must be influenced chiefly by the appearance of the fractures, which is strongly in favour of E. The cylinders not being driven out of A before bursting is against the gun, and the microscopic appearance of the particles examined all give the preference to E.

The general result then arrived at is—E, A, D, B, and C.

TABLE OF RESULTS.

| Letter of Gun | Order of Bursting | Bursting Charge | | | | | Total Quantity of Powder used | Total Weight of Shot | Total No. of Wads | Order from No. of Fragments | Order from Appearance of Fracture and Specimens | General Order derived from the foregoing |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Powder | Projectile | | Wads | No. of Rounds fired from each | | | | | | |
| | | | Cylinder | Shot | | | | | | | | |
| | | lbs. | | | | | | | | | | |
| A | 4 | 14 | 144 | $\frac{1}{24}$ pr. | 1 | 33 | 364 | 3,120 | 91 | 1 | 2 | 2nd |
| B | 3 | 14 | 144 | $\frac{1}{24}$ pr. | 1 | 32 | 350 | 2,952 | 90 | 5 | 4 | 4th |
| C | 1 | 10 | ... | 4 | 4 | 17 | 150 | 1,152 | 43 | 4 | 5 | 5th |
| D | 2 | 14 | 144 | $\frac{1}{24}$ pr. | 1 | 31 | 336 | 2,784 | 89 | 3 | 3 | 3rd |
| E | 4 | 14 | 144 | $\frac{1}{24}$ pr. | 1 | 33 | 364 | 3,120 | 91 | 2 | 1 | 1st |

Digitized by Google

Length of charge in bore at time of bursting of A, B, D, E—47·12 inches.

(Signed) F. EARDLEY WILMOT,
Lieut.-Col. R.A., Supt. R.G.F.

(Signed) C. W. YOUNGHUSBAND,
Captain Royal Artillery.

In addition to the foregoing we have the following analysis of the testing of the cast-iron used in the manufacture of the guns marked A, B, C, D, and E :—

Royal Gun Factories,
Woolwich, 11th July 1856.

*Report of the Testing of* 10 *Specimens of Cast Iron used in the Manufacture of Five Experimental* 24*-pounder Guns, burst in the Marshes at Woolwich, December* 1855, *supplied by Messrs. Fairbairn & Co.*

Two specimens were taken from the fractures of each gun—one at the breech, the other as near the muzzle as possible.

It may be remarked that the order of breaking corresponds with the trial the guns stood by the fire-proofs, and that the two guns (A and E)

| Nature | No. | Marks | | Specific Gravity | Breaking Weight per Square Inch of Section | Mean | | No. of Rounds before Bursting |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Specific Gravity | Breaking Weight | |
| | | | | | lbs. | | | |
| Bank Quay Foundry mixture | 1 | A | Breech | 7·2383 | 30,060 | 7·2105 | 28,516 | 33 |
| | 2 | | Muzzle | 7·1827 | 26,971 | | | |
| Pig iron remelted once, and then run into the mould in the ordinary way | 3 | B | Breech | 7·2290 | 29,426 | 7·2325 | 27,219 | 32 |
| | 4 | | Muzzle | 7·2360 | 25,013 | | | |
| Bank Quay Foundry mixture run from the copula, and remelted by desulphurised coke | 5 | C | Breech | 7·0976 | 18,657 | 7·0863 | 18,101 | 17 |
| | 6 | | Muzzle | 7·0751 | 17,544 | | | |
| As above, under a dead head pressure of 13 feet 9 inches | 7 | D | Breech | 7·2191 | 26,218 | 7·2032 | 25,954 | 31 |
| | 8 | | Muzzle | 7·1874 | 25,690 | | | |
| Pig iron remelted once, under a dead head pressure of 17 feet 3 inches | 9 | E | Breech | 7·2494 | 27,649 | 7·2441 | 28,516 | 33 |
| | 10 | | Muzzle | 7·2388 | 29,382 | | | |

Digitized by Google

which gave the greatest results in firing, and burst together after the same number of rounds, in their specimens gave exactly the same tensile strain.

(Signed) F. Eardley Wilmot.
Lieut.-Col. R. A., Supt. R.G.F.

---

## *Letter from Mr. Fairbairn to the President of the Ordnance Select Committee.*

Manchester; February 6, 1856.

Sir,

On referring to my own memoranda, and the granular character of the specimens of metal taken from the different guns immediately after bursting, I had arrived at the same conclusion in favour of E, with regard to the quality of the metal and the apparent density of its molecular structure, as Col. E. Wilmot. It will be borne in mind that this gun was of the same mixture (or nearly so) as A and the others which burst at an earlier period of the proof.

The gun A, cast with the ordinary head, was composed of—

| | cwt. | qrs. | lbs. | cwt. | qrs. | lbs. |
|---|---|---|---|---|---|---|
| Blaenavon No. 1 | 1 | 1 | 0 | | | |
| „ No. 2 | 11 | 2 | 14 | 42 | 2 | 14 |
| „ No. 3 | 19 | 3 | 0 | | | |
| Lillieshall No. 3 | . | . | . | 24 | 0 | 14 |
| Pontypool No. 3 | . | . | . | 11 | 3 | 0 |
| Gun-heads and scrap | . | . | . | 16 | 2 | 0 |
| | | | | 85 | 0 | 0 |

The gun E was cast under pressure from remelted iron of the following mixture. Head 17 feet 3 inches = a pressure of 50 lbs. per square inch on the top of the gun, which was filled up with gun-metal scrap.

| | cwt. | qrs. | lbs. | cwt. | qrs. | lbs. |
|---|---|---|---|---|---|---|
| Blaenavon No. 1 | 2 | 0 | 0 | | | |
| „ No. 2 | 15 | 0 | 0 | 43 | 0 | 0 |
| „ No. 3 | 26 | 0 | 0 | | | |
| Lillieshall No. 3 | . | . | . | 32 | 0 | 0 |
| Pontypool No. 3 | . | . | . | 15 | 0 | 0 |
| | | | | 90 | 0 | 0 |

I have not had an opportunity of ascertaining the specific gravities of

Digitized by Google

the different metals of the five guns experimented upon, as the specimens procured were not sufficient for that purpose. It is however desirable, under the circumstances, that these facts should be ascertained, as the specific gravity is to a great extent the measure of density; and from the experiments on the mechanical properties of hot and cold blast iron, undertaken by Professor Hodgkinson and myself, it was found that the powers of resistance of cast iron to strains followed in most cases the laws of density, and, if properly treated in the melting and temperature when run into the moulds, it was no unfair criterion of its powers of resistance to strain. In some of our best and strongest irons experimented upon, we have a specific gravity varying from 7·2 to 7·3;* and judging from these facts, I am of opinion that in order to ensure a superior quality of gun-metal, that the specific gravity should fluctuate between 7·2 and 7·3, according to the nature of the ores and fuel from which the metals are obtained.

As regards the material employed in the experimental guns, I am of opinion that all irons are improved by the second and third or fourth melting, according to the number and quality of the irons used. In gun E, which stood the severest tests, the iron was remelted from the pig, and then cast, as already described, with a head of 17 feet 3 inches in height. It was intended to have cast this gun from the fourth or fifth melting, or at that period when the metal was attaining its maximum of strength; but in the attempt to accomplish this, I found that the mixture attained its maximum power of resistance at the third melting. This was owing to the rigid nature of the material to commence with, most of the irons used being composed of strong No. 3, which attains, after very few meltings, the hard silvery state.

If a fluid No. 1 iron, containing a large proportion of carbon, had been used, the results would have been different, and the remeltings would in all probability have indicated increased strength and increased powers of resistance up to the fifth or sixth melting. In the experiments on Gartsherrie iron, it required eleven or twelve meltings before the maximum point of resistance was attained, but this was an extremely fluid soft-working iron, and therefore indicated greatly increased strength to the highest point of the remelting process. These changes will, however, vary according to the number of the irons and the quality of the ores from which they proceeded.

The subject of remelted iron is one of great importance to all classes, as well as the Government and the Public Service; and I avail

* See Table of Strength of Cast Iron Bars, 'Manchester Memoirs,' vol vi. (Second Series).

Digitized by Google

myself of this opportunity to direct attention to the circumstance, that although I have made the attempt to improve the quality of our irons by experimental research, I find that these experiments, although perfect and correct as far as they go, are nevertheless incomplete, and there is still wanting a continuation of the series on different irons, commencing with No. 1 and ending with No. 3 or No. 4 qualities. There is also wanting a much more extended series of investigations upon mixtures, rate of cooling, and all those combinations which in practice are known to improve the quality of the metal produced. This information would be of great value to the practical Founder and Engineer; and I trust that the Government will either establish a series of experiments on this subject, or afford the means of conducting them on a scale calculated to ensure correct and satisfactory results.

In conclusion, I have to remark that the gun marked E is an improvement upon the other four. It stood the same number of rounds as A, but with this difference, that it indicated a closer and stronger-grained metal, attributable, as I conceive, to the remelting of the iron in the first place, and subsequently by raising the head to increase the density of the mass by pressure.

To this latter circumstance, however, I attach less importance, as I have invariably found a closer and more compact combination of the materials of crystallisation by the remelting process.

I have the honour to be,
Sir,
Your faithful and obedient Servant,

WM. FAIRBAIRN.

To the President of the Select Committee on Ordnance.

Digitized by Google

# APPENDIX II.

Sir William Armstrong, in a letter to the 'Times,' June 26, 1865, seems to have abandoned all hopes of making guns of sufficient calibre and power to contend with targets similar to that representing the 'Hercules,' in which the Admiralty achieved so decided a success over the 300-pounder gun. Sir William states, in his letter to the editor, that the account given in the 'Times' of this experiment is isolated, namely, 'That although the victory remained conspicuously with the target, yet it is beyond a doubt that the very reverse of this result would have happened had the 600-pounder been tried against it instead of the 300-pounder.' 'I am very sorry,' says Sir William, very candidly, 'I cannot concur in this opinion. Powerful as the 600-pounder has proved itself to be, I confess I have great doubts of its obtaining the mastery over the "Hercules" target, unless the enormous charges already used with that gun be still further increased. Notwithstanding its past performances, it may not improperly be beaten by a target which, although only twice as heavy, is four times as strong as the "Warrior" target. I say four times as strong, because with the same quantity of material the resistance of a plate to the impact of a shot increases as the square of the thickness, so that the 9-inch armour of the "Hercules" target is, if the iron be equally good, four times as strong as the 4½-inch armour of the "Warrior." The backing also, from its vastly greater thickness, and the enormous quantity of iron framing combined with it, may be roughly estimated as stronger in the same proportion. Against this massive target three 12-ton shunt guns were fired, at a distance of only 200 yards, with charges varying from 45 lb. to 60 lb. of powder. In the instance of the 60-lb. charge, a steel shot of 300-lb. weight and 10½-inch diameter, struck the centre of the 9-inch armour-plate with a velocity of 1,450 feet per second. This is equivalent to an initial velocity of rather more than 1,500 feet per second, which is the full velocity due to the charge of 60 lb., and yet the blow was barely sufficient to break through the armour, and did not materially injure the backing. At short range the penetrating power of a steel shot is almost exclusively determined by the magnitude of the charge. The mode of rifling makes no difference, and the size of

Digitized by Google

the bore has but little influence, seeing that the greater velocity obtained with a large bore compensates for the diminished resistance opposed to the shot from a small bore. To increase the effect we have nothing to look to but increase of charge. Now, the service charge of the 600-pounder fired with a rifled shot is 70 lb., and I cannot anticipate that the penetration effected by this charge will be more than proportionate to that obtained with the 60-lb. charge fired from the 300-pounder gun. Judging from the effect produced, I incline to think that about double the power of 60 lb. of powder will be necessary to force a clear passage through the entire target at a distance of 1,000 yards, and if so, a gun that will bear a charge of 120 lb. of powder will be required to produce that effect. A smaller charge may suffice for the lodgment of a shell, but in any case I believe that more powder will be needed than has yet been used with our largest gun. It is much to be regretted that the delusive practice of designating the power of a gun by the weight of its shot, without reference to the charge of powder, should be continued. The force exerted obviously depends upon the quantity of powder effectively consumed, and it is well known that penetration is not materially assisted by the mere increase of the weight of the projectile. In rifled guns the shot may be lengthened or shortened, so as to be of any weight, and, consequently, according to the usual mode of designation, the gun may be called whatever the maker pleases. I have fired projectiles of 1,000 lb. from the 7-inch service breech-loader; but I should convey an absurdly-exaggerated idea of the power of that gun if I were to call it a 1,000-pounder. In your article upon the experiments against the "Hercules" target it is stated that 600-pounders are being made in scores upon the continent, and that from thirty to forty such guns have already been manufactured in this country for the Russian Government. This intelligence, I may observe, is strangely at variance with the statements of well-informed Russian officers who have recently visited this country officially on questions affecting artillery. But at any rate it would be highly desirable to have definite particulars of these so-called 600-pounders. The proof-charge applicable to guns of the class of the only 600-pounder which has been tried in England, would, according to the present Government regulations, be 87½ lb.; but no rifled guns, either for Russia or elsewhere, has been proved at Woolwich with more than 60 lb. of powder. These, therefore, are not such guns as our military authorities would rank as 600-pounders. Moreover, the number of rifled guns which have been proved at Woolwich, even with so high a charge as 60 lb., is not more than six, if indeed it be so many. Scores of 600-pounders ought to make some noise in the world, and I pause

Digitized by Google

to be satisfied of their existence before proceeding to ask after their performances.'

These remarks on the power of guns from such an authority as Sir William Armstrong show that, notwithstanding his great experience and the skill he has brought to bear on construction for the last five years, he is still in doubt as to the possibility of constructing a gun of sufficient strength to penetrate the 'Hercules' target. We have already noticed what we consider to be necessary in the construction of large guns; but the difficulty which presents itself is how to burn the requisite quantity of powder, and how to construct a gun strong enough to resist the charge. It has been demonstrated that if we increase the size of the gun we must also increase the charge of powder. The force, it will be observed, is not directly as the diameters, but as the squares, in order to give the desired and proportionate powers of penetration. It therefore follows that Sir William Armstrong is correct in his admission of the doubts and difficulties which surround this important question of obtaining any great increase in the power and strength of artillery.

On this question Mr. W. Cawthorne Unwin, B. Sc., has favoured us with a letter, which appeared in 'The Engineer,' vol. xx. p. 22, in which he remarks, with reference to Sir William Armstrong's conclusions, that—

'To the statement that the diameter of the shot in the case of steel projectiles has little influence on the penetration because "the greater velocity obtained with a large bore compensates for the diminished resistance in the plates opposed to the shot from a small bore," I am unable to assent. This implies that the work communicated to the shot per pound of powder increases in the same ratio as the bore, the resistance of the plates increasing in that ratio. On the contrary, I find that such data as are accessible prove the velocity communicated to be nearly constant for charges proportional to the weight of the shot in similar guns. Thus, to take a single instance from data given in Sir William's letter, comparing the old 68-pounder and the 300-pounder, I find that the work communicated to the shot is only 9 per cent. greater in the latter case than in the former; whereas the diameter of the shot, and consequently the resistance of the plates, is 33 per cent. greater. Hence since in practice the calibre of guns necessary to perforate armour-plates increases as the thickness of the plates augments, the charges required will increase in a higher ratio than that of the squares of the thickness of the plates; and, therefore, the point at which the targets will be found to be superior to the guns—the defence to beat the attack—will, by so much, be the sooner reached.

Digitized by Google

'For the sake of brevity, I shall simply refer here to the principles enunciated in two previous letters in vol. xiv. of the "Engineer," pp. 247, 248, taking the formulæ there given as proved.

'Let $w$ be the weight, $v$ the velocity, and $r$ the semi-diameter of a shot striking an armour-plate of the thickness $d$; then we have found—

$$w v^2 = \mathrm{T}\, r\, d^2. \quad \ldots\ldots\ldots\ldots \quad (1)$$

where T is a constant. But, with similar guns, having similar projectiles and charges having a constant ratio to the weight of the shot, the velocity is nearly constant. Hence—

$$d^2 = \mathrm{A}\frac{w}{r}$$

But $r$ varies as $\sqrt[3]{w}$

$$\therefore\ d^2 = \mathrm{B}\,\frac{w}{\sqrt[3]{w}} = \mathrm{B}\, w^{\frac{2}{3}}$$

$$\therefore\ d = \mathrm{C}\, w^{\frac{1}{3}} \quad \ldots\ldots\ldots\ldots \quad (2)$$

$$w = \mathrm{D}\, d^3 \quad \ldots\ldots\ldots\ldots \quad (3)$$

That is, for similar guns as above, the maximum thickness of armour-plate perforated will vary as the cube roots of the weights of the shot; or, in other words (on the present system), the denomination of the gun. And the weight of shot (the charge being in a constant proportion) required to penetrate different thicknesses of plate will be (not as the square, but as) the cubes of those thicknesses.

'To whatever extent it is ultimately found that the *vis viva* per lb. of powder increases with the bore, these formulæ will need to be corrected.

'If, instead of deducing the formula theoretically, we merely assume—

$$w = \mathrm{D}\, d^x$$

and deduce the value of $x$ from a series of experimental results, we have—

$$x = \frac{log\ w - log\ w_1}{log\ d - log\ d_1}$$

And applying this to the Shoeburyness results on cast-iron shot, and averaging the values obtained, we get $x = 2{\cdot}47$. So that—

$$d = \mathrm{C}\, w^{\frac{2}{5}} \quad \ldots\ldots\ldots\ldots \quad (4)$$

$$w = \mathrm{D}\, d^{\frac{5}{2}} \quad \ldots\ldots\ldots\ldots \quad (5)$$

'I have calculated the value of the constants C and D for two cases.

Digitized by Google

'First, with cast-iron Armstrong shot, fired from Armstrong rifled guns, with charges one-eighth the weight of the shot—

$$d = 0{\cdot}644\, w^{\frac{2}{5}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$w = 3\, d^{\frac{5}{2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

'Second, for flat-ended cylindrical steel charge, the charge being one-fifth that of the shot, as in the case of the 300-pounder mentioned by Sir William Armstrong—

$$d = 1{\cdot}05\, w^{\frac{2}{5}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

$$w = 0{\cdot}9\, d^{\frac{5}{2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

'To test these results let us assume that the resistance of the combined structure, known as the "Warrior" target, with 4½-in. facing, was equivalent to that of an unbacked 6-in. plate, and that of the "Hercules" target, with 9-in. facing, is equivalent to that of a 12-in. plate. This estimate, if not exact, cannot be very far from the truth; and, relatively, the resistance of one being four times that of the other, is the same as given by Sir William Armstrong. Then for cast-iron shot (formula 7) we find that a 264-pounder, with 33 lb. charge, will be required to penetrate the "Warrior" target (1), and a 1,500-pounder, with 187 lb. charge, to penetrate the "Hercules" target.

'Similarly, with steel flat-fronted shot, the "Warrior" will require an 80-pounder, with 16 lb. charge (2), and the "Hercules" target a 450-pounder, with 90 lb. charge.

'To be similar to the 300-pounder the 600-pounder should carry a charge of 120 lb. It is said to have been fired with 90 lb. Now, looking to the fact that the shot is larger than that of the normal 450-pounder in the calculation above, and will, therefore, require a greater charge, I am of opinion that if ever it is used against the "Hercules" target with a charge of 100 lb. of powder it will perforate the target (3). If 70 lb. of powder in a 600-pounder gun, as given in Sir William's letter, represents the limit of safe loading, then a somewhat *larger charge still* will be required; so that these calculations agree with and confirm the practical conclusion at which Sir William has arrived, that a gun carrying 120 lb. of powder will be necessary to penetrate that target, and this agreement in the result may lead him to be more disposed to accept the conclusion that the charges required to penetrate plates do not increase as the squares of the thicknesses of the plates, but in a higher ratio.

'Formula 8 gives for the penetration of the 300-pounder, with 60 lb. charge and steel shot, a thickness of 10½ in. Now, Sir William

Digitized by Google

Armstrong states that that gun actually perforated the 9-in. facing of the "Hercules" target, doing some, if not much, damage to the backing. The agreement of fact and formula is as close as could be expected.

'(1.) The 300-pounder, with a 150 lb. cast-iron shot, 10½ in. diameter, penetrated the "Warrior" target with 40 lb. and 50 lb. charges. The shot of the 264-pounder, by assumption, would have been only 9¼ in. diameter.

'(2.) The 80-pounder shot would be 6¾ in. diameter, so that this result agrees nearly with the experiments with Whitworth shell against the "Warrior" target.

'(3.) It was once fired with 70 lb. against an 11-in. unbacked plate, but the plate palpably gave way by transverse fracture, affording a strong confirmation of the views I have expressed on the mode of yielding of thick plates.

'For the formulæ in this letter it will be seen that $r = 0{\cdot}75\sqrt[3]{w}$ nearly.'

### *The Fouling of Iron Ships.*

The subject of fouling and the adhesion of barnacles to the hulls of iron vessels has been, since their first introduction, a source of trouble and of difficulty for which no effectual remedy has been applied. On enquiry at Liverpool as to the effect of fouling of iron vessels trading between that port and Calcutta, the author was informed by Captain Campbell, of the 'Kenyon,' that he had no trouble with his ship, as the plates were left perfectly clean after being a short time in the fresh water of the Hooghly. If this be the case, why not have docks or basins filled with fresh water at the different ports, into which vessels covered with mollusca might be floated, for the purpose of cleansing and removing the obstructions to which they are subject when built of iron? It is an easy mode of getting quit of the nuisance, and that without injury to the plates.

Digitized by Google

# INDEX.


AME

AMERICA, armour-plated ships of, 226, 230
Armour-plated ships, the first, 103
— examination into the various thicknesses and different forms and conditions of plates of iron for ships, 104, 106
— comparison of results of experiments on armour-plates, 178
— with backing, 181
— without backing, 182
— Mr. Fairbairn's targets, 182
— details of the armour-plated vessel 'Warrior,' 218
— and of the 'Bellerophon,' 213
— details of American armour-plated ships, 226 *et seq.*
— success of the 'Hercules' target over the Armstrong 300-pounder gun, 299
Armstrong, Sir William, description of his guns, 150
— his letter to 'The Times' on the success of the 'Hercules' target over his 300-pounder gun, 299
— Mr. Unwin's remarks, 301

BEAMS, iron-jointed, endurance of, when subjected to alternate strains, 13. *See* under Material, the strength of
'Bellerophon,' details of the construction of the, 213
'Black Prince,' the, 103
Blakeley, Captain, his system of ordnance, 150, 151

COM

Boilers of Watt's early steam-engines, 1
— rolled plates of iron for, 1
— haystack form of, 1
— Watt's waggon-shaped, 2
Breech-loading ordnance, introduction and abandonment of, 104

CANAL BOATS, iron, first construction of, 2
Canals, Mr. Fairbairn's experiments on the absence of surge on, at high velocities, 3
— Messrs. John and Macgregor Laird, their iron boats for the Irish canals, 3
— introduction of steam on the locomotive principle, 3
Cast-iron plates. *See* Plates
Clark, Mr. Edwin, abstract of his investigations of resistances to flexure, 55
Clyde, energy and enterprise of the iron ship builders on the, 5
Coles, Captain, his introduction of the turret-system into the construction of ships of war, 116
— comparison of his system with that of Mr. Reed, 117
Compression of various kinds of materials, table of experiments of resistance to, 48
— the law of fracture of columns, 49
— — Prof. Hodgkinson's experiments, 49
— — the author's experiments, 50
— law which seems to govern short




Digitized by Google

COM

Compression—*continued*
bolts or columns of two diameters in length, 50
— shortening or compression of wrought and cast iron, 51
— abstract of Professor Hodgkinson's experiments on the resistance of plates of wrought iron to a crushing force, 53
— resistance of circular and rectangular tubes to the force of compression, 54
— abstract of Mr. Edwin Clark's investigations of resistance to flexure, 55
Cort, Mr., his invention of rolling plate and bar iron, 1

DECKS of iron ships, sectional form of beams for, 91
Deflexion of beams, 282–284
Displacement of a ship, 10
— rule for finding the displacement, 11 *note*
Ductility of iron and other metals, 20, 23
— at a low temperature, 31

FAIRBAIRN, Mr., his experiments made for the Forth and Clyde Canal Company, 3
— his iron ship building establishment at Millwall, 4
— his letter to the Admiralty on iron-plated ships, 126
— his iron targets, 182
Fouling of the hulls of iron vessels, 92, 116, 235, 304
Fracture, law of, of crystalline substances, 49
— results observable at Shoeburyness, 49
— Professor Hodgkinson's investigations, 49
Frames and ribs of iron ships, 82
— strongest and most suitable, 82
— experiments on beams and angle-iron, 83–90
France, armour-plated and iron ships of, 234

IRO

GRANTHAM, Mr., his iron boats, 2 *note*
— his remarks on defective riveted joints, 43
— his attention paid to the oxidation and fouling of the hulls of iron vessels, 116

'HERCULES' target, its success over the 300-pounder gun, 299
Hodgkinson, the late Professor, his investigations of the law of fracture, 49
Horsley Company, builds the 'Aaron Manby,' 2
Houston, Mr., of Johnstone, his light canal boat, 2

INGOTS of iron, 19
Iron ships, a short history of the rise and progress of building, 1
— Cort's invention of rolling plate and bar iron, 1
— iron canal boats, 2
— the Horsley Company's 'Aaron Manby,' 2
— Mr. Houston's light canal boat, 2
— Mr. Fairbairn's experiments on the law of traction and the absence of surge at high velocities on canals, 3
— his iron boats, 3
— Messrs. John and Macgregor Laird's iron boats for the Irish canals, 3
— their 'Alburka,' sent out for the exploration of the Niger, 4
— numerous improvements which have since taken place, 4
— recent progress, 5
— remarks on iron ships of war, 5
Iron, on the properties of, considered as a material for ship building, and the resistance of iron plates to the force of extension, 18
— advantages of wrought iron, as a material for the construction of ships, over every other kind of material, 18
— on the properties of iron considered as a material for ship building, 19

Digitized by Google

IRO

Iron—*continued*
— — extent and variety of iron ores, 19
— — states of the iron received by the iron ship builder, 19
— property of tenacity, 20
— — experiments on the strength of plates when torn asunder by a direct tensile strain in the direction of the fibre, and when torn asunder across it, 21
— properties of ductility, elongation, &c., 20, 22, 23
— — experiments on the mean tensile strength of iron plates, or statical breaking strain, 23
— — — correspondence in density and tenacity, 24
— — experiments on the ultimate elongation per unit of length, 25
— — Mr. Mallet's co-efficient, or work done in causing rupture, corresponding with resistance to impact, 26
— — increase of dynamic resistance with the thickness of the plates in a higher ratio in the iron plates than in the homogeneous metal plates, 27
— — ratios of dynamic resistance between iron and steel, 27
— — additional observations on the ultimate elongations per unit of length, 29
— — results of Mr. Lloyd's experiments on the tensile strength of S C bars, 30
—. on the strength of the joints of plates when united by rivets, as compared with the strength of the plates, 31
— — punching, 32
— — riveting, 34
— the resistance of plates as applied in different forms to the force of compression, 47
— — flexure, crushing, and compression, 48
— oxidation of iron, and the influence of constant use and of vibration, 92
— effect of salt water upon cast and wrought iron, 92
— results of experiments with American

MAT

Iron—*continued*
cast irons as compared with those of Great Britain, 137, 138
— on the practical construction of iron ships, 197
Iron and wood, combination of, in the construction of ships, 71
— comparative values of iron and timber submitted to a tensile strain, 72
— defects of wooden constructions, 73
— resistance of wrought-iron plates to bursting, 77
— experiments to determine the resistance of plates of wrought-iron to a force tending to burst them, 78
— experiments to determine the resistance of planks of timber to a force tending to burst them, 80
— comparative strength of iron and timber under a compressive strain, 81
— abstract of results obtained from experiments, 93
— different methods of constructing ships of iron and wood, 95
— — Mr. M'Laine's principle of uniting iron and wood for purposes connected with the navy, 97
Iron Plate Committee, appointment of the, 104

'LA GLOIRE,' the first iron-plated ship of war, 103
Laird, Messrs. John and Macgregor, their iron boats for the Irish canals, 3
— and for the exploration of the Niger, 4

MALLET, Mr., his co-efficient, the modulus of resilience, 25, 26
Material, the strength of, theoretically and practically considered in relation to the construction of iron ships, 237
— elongation and compression, 237
— the neutral axis of a beam, 239
— conditions of transverse rupture, 241
— to change the axis of moments, 243



Digitized by Google

MAT

Material—*continued*
— transverse strains produced on beams under various conditions, 244
— strengths, &c., of beams, 254
— when the neutral axis passes through the centre of the section, 255
— hollow rectangular beams, and beams with double flanges, 256
— cylindrical beams, 258
— elliptical beams, 261
— oblique lined beams, 262
— when the neutral axis does not pass through the centre of the section, 267
— strength of an iron ship, 273
— strengths of similar beams, 277
— beams of greatest absolute strength, 279
— deflexion of beams, 282
M'Laine, Mr. Alexander, his end-on system of construction of ships of war, 122
Merchant ships, iron, on the practical construction of, 199
— the cellular construction and double bottom, 200
— position, form, thickness, &c., of the material which enters into the construction of iron ships, 201
— how the different parts are prepared and united in order to attain their full value in combination, 203
— — for clippers, 203
— — for steamers with screw propellers, 206
— on the practical construction of iron ships of war, 206. *See* War, Ships of
Moment of inertia, 262–269

NAPOLEON III., his suggestion of iron-clad ships, 6, 103
'Nauset,' the light-draught American monitor, 228
Navy, remarks on the iron ships of war, 5, 6
'New Ironsides,' details of the American iron-clad vessel, 226

ORD

ORDNANCE, necessity for rifled, 104
— introduction and abandonment of breech-loaders, 104
— effects of cast-iron shot on wrought-iron plates, 108
— and of wrought-iron shot on wrought-iron plates, 109
— the proper weight and size of guns an armour-plated ship is calculated to carry, 109
— on the properties of cast and wrought iron and steel as materials for the construction of ordnance, 135
— Major Wade's experiments 'On the Strength and other Properties of Metals for Cannon,' 136
— American hollow cast-iron guns, 139
— — results of proof charges, 142
— — causes from which to trace the differences which ensued in the cases of rupture, 143
— endurance of cast-iron, 145
— extreme proof of this endurance, 146
— question of the longevity of the strains in guns, 147
— introduction of new guns, 149
— — description of Sir William Armstrong's guns, 150
— and of Mr. Whitworth's guns, 151
— those of Captain Blakeley, Mr. Mackay, and Captain Palliser, 151
— importance of the observation of the laws of cooling and crystallization, 152
— on the properties of armour-plates, and their resistance to shot at high velocities, 153
— mistakes in regard to the weight and power of rifled ordnance, 167
— effect of steel shot on armour-plates, 169
— on the impact and resistance of shot and shells fired against armour-plates, 170
— — properties of different kinds of shot, 171
— — applications of general formula to the experiments at Shoeburyness, 175
— — results of trials with Whitworth's steel projectiles, 177

Digitized by Google

ORD

Ordnance—*continued*
— comparison of results of experiments on armour-plates, 178
— quality of shot, 183. *See* Shot
— report of the comparative proof of five experimental 24-pounder guns, 289
— — report of the testing of ten specimens of cast-iron used in the manufacture of these five guns, 295
— — Mr. Fairbairn's letter to the President of the Ordnance Select Committee, 296
— success of the 'Hercules' target over the Armstrong 300-pounder gun, 299

PALLISER, Captain, his case-hardened shot, 183
Pig iron, 19
Plates of iron, Cort's invention of rolling, 1
— on the strength of, as compared with the strength of the joints of plates when united by rivets, 31
— punching, 32
— riveting, 34
— experiments, 36
— general summary of results, 39
— the resistance of plates as applied in different forms to the force of compression, 47
— flexure, crushing, and compression, 48
— strength and distribution of the material of wrought-iron plates and frames as applied to the construction of iron ships, 64
— experiments to determine the resistance of plates of wrought iron to a force tending to burst them, 78
— appointment of the Iron Plate Committee, 104
— Sir B. Hawes's instructions to the Committee, 104, 105
— *See* War, Ships of
Price, Dr., his cast-iron shot, 183
— results of experiments with, 183
Punching, for rivets, 32
— half-blind punching, 33

SHO

RAM vessels of war, 116, 134
Rankine, Dr., his investigation of the question of the strains of ships, 12
Reed, Mr', his appointment as Naval Constructor, 111
— his system of construction of ships of war, 111
— principal important features of his plan, 113–115
Resilience, modulus of, the co-efficient of strength so called, 25
— table of work done in causing rupture, corresponding with resistance to impact, 26
Ribs and frames of iron ships. *See* Frames
Rifled ordnance, introduction of, 104
Riveting, 34
— overlap single-riveted joint, 34
— double-riveted joint, 35
— results of experiments, 36–40
— the mode of riveting introduced into the construction of the Britannia and Conway Tubular Bridges, 40
— strength of riveted joints, 41
— defects of riveted joints, 43
Rivets, strength and durability of, 31
— punching, 32
— form, strength, and proportion of rivets in joints requiring to be steam or watertight, 45
Rolling plate and bar iron, Cort's invention of, 1
Russell, Mr. Scott, his form and construction of ships, for war or commerce, 116

SAFE working load of wrought iron, 14
Salt water, influence of, on the hull of an iron ship, 92
Shot, effect of steel, on armour-plates, 169
— on the impact and resistance of shot and shells fired against armour-plates, 170
— properties of different kinds of shot, 171

Digitized by Google

SHO

Shot—*continued*
— quality of shot, 183
— — shot prepared by Dr. Price and Captain Palliser, 183
— advantages of decarbonisation, 186
— effects of statical pressure on different kinds of shot to a force tending to crush them, and the forms they assume under pressure, 186
— results of an experiment with a section of the 'Warrior' target, showing the effect of the shot fired, and the injury done to the shot, 193
— the conditions desirable in projectiles, 195, 196
Strains to which a ship is subjected when afloat, 8
— when supported on two waves, one at the bow and another at the stern, 9
— when supported on one wave passing from the bows and stern to the centre of the ship, 9
— vessels floating in still water, 10
— strains produced by inequalities of displacement or immersion, apart from the dynamic effect of a mass of water in a state of violent motion, 11
— Dr. Rankine's investigation of the subject of the strains of ships, 12
— endurance of iron-jointed beams subjected to alternate strains, 13
— strains to which a ship is subjected when stranded, 16
— in guns during cooling, 143
— longevity of these strains, 147

TABLES:—Iron plates and bars, and riveted joints
— I. Results of iron plates torn asunder in the direction of the fibre and across it, 21
— II. Summary, giving mean tensile strength of iron plates, or statical breaking strain, 23
— III. Summary, giving the ultimate elongation per unit of length, 25
— IV. Mr. Mallet's co-efficient, or work done in causing rupture, corresponding with resistance to impact, 26

TAB

Tables—*continued*
— V. Progressive increase of dynamic resistance with increased thickness of plates, 27
— VI. Proportional ratios of the dynamic resistance of iron and homogeneous metal, 27
— VII. Corresponding results obtained in the trials with ordnance, 28
— VIII. Mr. Lloyd's summary of experiments on the tensile strength and elongation of S C bars, 30
— IX. General summary of results of experiments as to the cohesive strength of plates, and strength of double and single-riveted joints, 39
— X. Strongest forms and best proportions of rivets and riveted joints, as deduced from experiments and actual practice, 45
— XI. On compression, &c., of various kinds of materials by statical pressure, 48
— XII. Resistance of plates of wrought iron to a crushing force, the ends of the plates being turned flat, and perfectly bedded against the parallel planes, between which they were compressed, 53
— XIII. Resistance of circular tubes, all 10 feet long, to a force or compression in the direction of their length, 54
— XVI. Resistance of rectangular tubes, all 10 feet long, to a force or compression in the direction of their length, 55

*Iron and Timber in Ship Building.*
— I. Comparative resistances of iron and various kinds of timber submitted to a tensile strain, 72
— II. III. IV. Tensile strength of timber sheathing, and of the wood composing it, 74, 76
— V. The resistance of wrought-iron plates to a force tending to burst them, 78
— VI. The resistance of planks of

Digitized by Google

TAB
Tables—*continued*
timber to a force tending to burst them, 80
— VII. Comparative strength of iron and timber under a compressive force, 81
— VIII.–XII. Experiments to ascertain the strengths of uniform wrought-iron beams of different forms to support the sides and other parts of vessels, the beams having their ends placed upon props and being loaded in the middle, 85–90

*Ordnance.*

— I. Results of experiments on the tensile strength of American iron used in the construction of ordnance after repeated meltings, 137
— II. Similar experiments on British iron, 138
— III. Extreme proof of the endurance of American cast-iron ordnance, 146

*Armour-plates.*

— I. General summary of results of experimental tests on the tension and compression of French and English armour-plates, 158
— II. Summary of experiments of indentation, 159
— III. General summary of punching, 160
— IV. Nature of ordnance, weight of shot, &c., fired against the 'Lord Warden' target, 162

*Experiments on Impact.*

— I. Comparison of general formula with experiments on armour-plates at Shoeburyness, 176
— II. Comparison of results of experiments with Whitworth's steel projectiles, with the formula deduced from the wall-piece, 177
— III. Comparison of work done in foot pounds on different targets, 179
— IV. Summary of results, 181
— V. Experiments with plates supported by backing, 181

WAR
Tables—*continued*
— VI. Mean value of indentation of plates without backing, 182
— VII. Summary of results of work done by statical pressure on cast, wrought-iron, steel, and lead shot, 189
— VIII. Report of an experiment, showing the effect of shot fired against the 'Warrior' section,—target No. 14,—and also the injury done to the shot, 193

*On the Construction of Iron Ships.*

— I. Showing the size, tonnage, armament, &c., of some of the armour-plated vessels of Her Majesty's navy, 224

*Appendix I.*

— I. The diameter, weight, bursting charge, &c., of five experimental 24-pounder cast-iron guns, 294
— II. Method adopted in casting, tensile strength, specific gravity, &c., of the iron, 295

Tate, his chapter on the strength of material considered in relation to the construction of iron ships, 237
Tenacity of iron, property of, 20
Turret-system of ships of war, introduction of, 116
— details of the American 'Chickasaw,' 227
— details of the American 'Nauset,' 228

UNWIN, Mr. W. Cawthorne, his remarks on Sir W. Armstrong's letter to the 'Times' respecting the 'Hercules' target and his 300-pounder gun, 301

WADE, Major, his series of experiments 'On the Strength and other Properties of Metals for Cannon,' 136
War, ships of, on the varied forms of construction of, and their armament, 103
— 'La Gloire,' the 'Warrior,' and the 'Black Prince,' 103

Digitized by Google

WAR
War, ships of—*continued*
— rifled ordnance, 104
— appointment of the Iron Plate Committee, 104
— the armour-plates of the 'Warrior,' 106
— Mr. Whitworth's hardened steel shell fired through a 4½-inch plate, 107
— experiments as to the law of resistance of plates of different thicknesses to projectiles fired point-blank at short distances, and at right angles to the plate, 107
— effects of cast-iron shot on wrought-iron plates, 108
— effects of wrought-iron shot on wrought-iron plates, 109
— proper weight and size of guns, and the weight of armour-plate a ship is calculated to carry, 109
— Mr. Reed's system of construction of ships of war, 111
— ram vessels, 116
— Captain Coles's turret-ships, 116
— comparison of his and Mr. Reed's plan, 117
— Mr. Alexander M'Laine's end-on system of construction, 122
— results of American practice with armour-plated ships, 124, 125
— the author's letter to the Admiralty respecting armour-plated ships, 126
— his proposed system of armour-plated ships, 130
— character of the armour-plate manufacture at the commencement of the labours of the Iron Plate Committee, 135
— on materials for the construction of ordnance, 135
— on the properties of armour-plates, and their resistance to shot at high velocities, 153
— Admiral Porter's report on the monitor and ironsides classes of vessels, 153–155
— comparison of the value of the turret and broadside vessels, 155
— effects of experiments on armour-plates made before and during the existence of the Iron Plate Committee, 156, 157
— summaries of results of experimental tests applied to French and English armour-plates, 158–160
— — general summary of tension and compression, 158
— — summary of indentation, 159
— — general summary of punching, 160
— — experiments on the 'Lord Warden' target, 161
— effects of steel shot on armour-plates, 169
— on the impact and resistance of shot and shells fired against armour-plates, 170
— — properties of different kinds of shot, 171
— — laws relative to the resistance of iron plates to a force tending to rupture them, 173
— — formulæ for the penetration of wrought-iron plates by projectiles, 173
— — application of general formula to the experiments at Shoeburyness, 175
— importance of iron in naval shipbuilding, 197
— on the practical construction of ships of war, 206
— — considerations required in building vessels of war, 207
— — — magnitude or tonnage, 208
— description of the proposed shield ship, 209
— — — general principles of construction, 210
— — — — details of the 'Penelope,' 211
— — — — details of the 'Bellerophon, 213
— — — — details of the 'Warrior,' 218
— — — effects of a water-shield running parallel with the armour-plating all round the ship, 221
— dimensions, tonnage, armaments, and other conditions of some of the leading

Digitized by Google

WAR

War, ships of—*continued*
vessels of Her Majesty's iron-clad fleet, 224
— details of some of the American iron-clad ships, 225
— — the 'New Ironsides,' 226
— — the turret-vessel 'Chickasaw,' 227
— — the light-draught monitor 'Nauset,' 228
— — American armour-plated sea-going vessels, 230
— on the comparative merits of ships of war, 231
— — iron *versus* timber, 231, 235
— — what in our opinion constitutes aggression of the most formidable description, 232
— — the four proposed swift vessels with heavy armaments, 233

WRO

War, ships of—*continued*
— — what has been done in France and America, 234
— fouling of the hulls of, 92, 116, 235, 304
'Warrior,' the, 103
— details of her armour, 106
— details of the construction of this vessel, 218
Watt, James, materials of which his first boilers were made, 1
— his waggon-shaped boilers, 2
Whitworth, Mr., his hard steel shell fired through a 4½-inch plate, 107
— description of his system of ordnance, 151
— results of trials with his steel projectiles, 177
Wrought-iron plates. *See* Plates

LONDON
PRINTED BY SPOTTISWOODE AND CO.
NEW-STREET SQUARE

Digitized by Google

Digitized by Google

## BY THE SAME AUTHOR.

# USEFUL INFORMATION FOR ENGINEERS:

**Being a First Series of Lectures delivered before the Working Engineers of Yorkshire and Lancashire. With Appendices, containing the Results of Experimental Inquiries into the Strength of Materials, the Causes of Boiler Explosions, &c.**

**Fourth Edition, Revised; with Plates and Woodcuts. Crown 8vo. Price 10*s.* 6*d.***

'Mr. Fairbairn's name is a guarantee for the soundness of this work. It treats of steam, fuel, and boilers,—the working classes, as they will one day be called; with an appendix on wrought iron,—the workman's jacket stuff. Though a professional book, it is as much adapted for the general reader as such a book can be.' ATHENÆUM.

# USEFUL INFORMATION FOR ENGINEERS,

**Second Series: Containing Experimental Researches on the Collapse of Boiler Flues and the Strength of Materials, and Lectures on Popular Education and various Subjects connected with Mechanical Engineering, Iron Ship-building, the Properties of Steam, &c.**

**With Plates and numerous Woodcuts. Crown 8vo. Price 10*s.* 6*d.***

'All Mr. Fairbairn's papers are written in a clear and popular style, and, as far as possible, divested of mechanical technicalities, so that they may be read with interest not only by amateur or professional engineers, but by the general public. Much of the information conveyed possesses a wider application than is suggested by the title, and the work is really an attractive one even to the ordinary reader. .... It is not too technical nor abstruse, and may be read with pleasure and profit by all who take an interest in either civil or mechanical engineering.' GLASGOW HERALD.

# A TREATISE ON MILLS AND MILLWORK.

**Second Edition, carefully revised, of both Volumes.**

**Vol. I. *The Principles of Mechanism and Prime Movers;* with 8 Plates and 176 Woodcuts: Vol. II. *Machinery of Transmission, and the Construction and Arrangement of Mills;* with 10 Plates and 157 Woodcuts. 2 vols. 8vo. Price 32*s.* cloth, or separately 16*s.* each volume.**

'This valuable work is now complete, and we doubt not that it will receive from engineers the reception to which its merits fully entitle it. It is a book which no engineer's library should be without.' SPECTATOR.

'The whole subject is so ably and systematically treated that we believe there is no question connected with millwork upon which the practical man is likely to require information, that he will not find fully elucidated in Mr. Fairbairn's work. It is a work which commends itself to all engaged in the engineering profession.' MINING JOURNAL.

'The entire work forms a most valuable book of reference. The engineer, even if inexperienced in the construction of any particular class of machinery, need never be at a loss for the correct solution of a minute question of detail. The tables interspersed give the speeds of all the machines treated of, from the smallest to the largest; while general information is put before the reader in a pleasing and accessible form. We cordially recommend the book to the mechanical engineer as one of the best of its kind.' MECHANICS' MAGAZINE.

'As the most successful and most extensive master-millwright in the world, Mr. Fairbairn has done good service to the profession of engineering by the publication of this work. The subject is one on which there has been a singular dearth of published information; most other important branches of engineering have been treated at length by more or less able authors, but the mysteries of the millwright's craft have been hitherto preserved mainly in oral traditions and empirical rules. No fitter person than Mr. Fairbairn could have been found to give this floating information a shape. Commencing his work as a millwright some fifty years ago, he found the practice of mill-work in a most primitive condition. By the application of new principles, by the concentration of motive power, the substitution of cast-iron wheel-work for the old and cumbrous forms of wooden gear, the improvement of water-wheels by the invention of ventilating buckets, the use of the steam-engine as a prime mover, and last, not least, the introduction of wrought-iron shafting of small diameter, he brought about just such a revolution in the millwright's art as the increasing commercial activity of his time demanded.' JOURNAL of SCIENCE.

London: LONGMANS, GREEN, and CO. Paternoster Row.

Digitized by Google

## BY THE SAME AUTHOR.

# ON THE APPLICATION
OF
# CAST AND WROUGHT IRON
TO
# BUILDING PURPOSES.

**Third Edition, partly rewritten, corrected throughout, and enlarged, with the Addition of a short Treatise on Wrought Iron Bridges.**

**Illustrated by 6 Plates engraved on Steel and 118 Woodcuts.**

**8vo. price 16s.**

---

THIS work, which is entirely of a practical character, has been carefully revised by the Author; and the Third Edition comprises, in addition to its former contents, an account of the most recent improvements in fire-proof buildings, the employment of wrought-iron instead of cast-iron beams, and experimental researches on the effects of vibration on beams, girders, and bridges. The general contents are disposed in Four Sections, as follows. I. The adaptation of cast-iron beams for the support of the floors of mills, warehouses, and public buildings; including the experiments of the Author and the late Professor HODGKINSON, establishing formulas for the guidance of the Architect and the Engineer. Also experiments to determine the value of trussed beams of cast and wrought iron, and wrought iron and wood. The influences of time and temperature on these constructions are considered, and in a tabulated form are given the results of experiments on cast-iron derived from frequent meltings and re-meltings. SECTION II. contains a description of wrought-iron beams, and their adaptation for building purposes, showing their superior strength, security, and durability over cast-iron beams. SECTION III. treats of the construction of fire-proof warehouses and buildings of that important class, together with practical details relative to their security as fire-proof structures. SECTION IV. is almost exclusively devoted to Bridges composed of Wood, Stone, and Iron, and those other constructions denominated Tubular, Tubular Girder, Lattice, Warren, and Plate Bridges. The proportions and necessary formulas for calculating the strength of each of these classes of Bridges are given, together with details of numerous examples in actual existence. An APPENDIX to the work (now first added) includes an account of the Bridge intended to cross the Rhine at Cologne; followed by some remarks on the fall of a Cotton Mill arising from defective beams and defective construction.

London: LONGMANS, GREEN, and CO. Paternoster Row.



Digitized by Google

Digitized by Google

Digitized by Google

Digitized by Google

UNIVERSITY OF CALIFORNIA LIBRARY
BERKELEY

Return to desk from which borrowed.
This book is DUE on the last date stamped below.

ICLF (N)

6Apr52DP
23Mar52
23Jan'63gc
REC'D LD
JAN 17 1963
REC'D LD
APR 23 1963
8Dec'64JS
Seaman

JAN 8 1965
REC'D LD
JAN 4'65-11 AM
SEP 29 1966 87
RECEIVED
SEP 30'66-1 PM
LOAN DEPT.
APR 28 1969 87
OCT 20 1972 95

LD 21-95m-11,'50(2877s16)476

Digitized by Google

U.C. BERKELEY LIBRARIES
C006795407

Digitized by Google

Digitized by Google